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AFAPL-TR-70-10
VOLUME I

EVALUATION STUDY OF THE OXIDATION-CORROSION CHARACTERISTICS OF AIRCRAFT TURBINE ENGINE LUBRICANTS

J. P. Cuellar
B. B. Baber

Southwest Research Institute

TECHNICAL REPORT AFAPL-TR-70-10, VOLUME I

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VOLUME I

EVALUATION STUDY OF THE OXIDATION-CORROSION CHARACTERISTICS OF AIRCRAFT TURBINE ENGINE LUBRICANTS

J. P. Cuellar
B. B. Baber

FOREWORD

This report was prepared by Southwest Research Institute, 8500 Culebra Road, San Antonio, Texas, under Contract F33615-69-C-1295, Project No. 3048. The work was administered by the Lubrication Branch, Air Force Aero Propulsion Laboratory (AFAPL), Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The project engineers were Messrs. G. A. Beane, L. J. DeBrohun, and H. A. Smith (APFL).

This report covers one phase of work performed under the subject contract. This report was submitted by the authors in January 1970.

This technical report has been reviewed and is approved.

H. F. JONES
Chief, Lubrication Branch,
Fuel, Lubrication, and
Hazards Division
Air Force Aero Propulsion
Laboratory

ABSTRACT

Results of oxidation-corrosion test evaluations on numerous aircraft turbine engine lubricants are given. Lubricant types include those related to specifications MIL-L-7808, MIL-L-9236, MIL-L-23699, and MIL-L-27502, as well as a number of experimental-type fluids such as polyphenyl ethers. Blends of selected lubricants were also examined. Test conditions were varied extensively in the study, with emphasis on the parameters of time, temperature, airflow, metals, and reflux of condensable sample vapors. A major objective in investigations with conventional, ester-type lubricants was a comparison of relative performance for test series of short duration and high temperature versus long duration (26 days) and relatively low temperature. In addition, several experimental-type fluids were evaluated in a test series over a temperature range of 600 to 680°F. This investigation was mainly concerned with performance effects due to variation of metal types in the corrosion specimen set. The applicability of electro-cleaning of metal specimens was also explored with regard to improvement of the repeatability of corrosion data. Volume II of this report contains a compilation of the individual test data sheets for all tests reported herein.

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SECTION I

INTRODUCTION

This report describes studies carried out to investigate the oxidation and corrosion characteristics of various Air Force coded lubricants intended for application in aircraft gas turbine engines. The oxidation-corrosion test in its various forms is normally the initial screening tool in the laboratory evaluation of candidate lubricants. The relatively low cost and ease of performance make the test an especially valuable tool in that numerous fluids and test conditions may be investigated for the intended service. Basically, the test examines lubricant deterioration at selected temperatures using an oxidizing atmosphere (air) and selected metal specimens. Fluid performance is measured by changes in sample viscosity and acidity. Metal specimen attack is evidenced by coupon weight change per unit surface area.

Test data presented herein were obtained under widely varying conditions and procedures. Evaluations conducted with conventional and advanced ester-type lubricants covered a range of temperatures from 347 to 464°F and durations from 48 hr to 26 days. Results were also obtained for several experimental lubricant formulations at sample temperatures up to 680°F. For most test series, conditions were varied extensively with respect to test time, temperature, airflow rate, metal specimen types, and reflux or nonreflux of condensable vapors.

In the later stages of this effort, the concept of lubricant breakpoints was introduced. This property, defined in detail in a subsequent section of this report, was applied to both 100°F viscosity change and neutralization number change. The breakpoints are expressed as a period of test time required to reach a specific rate of sample degradation, and are intended as one type of measure of the lubricant's "useful life." Lubricant breakpoint may be considered as an attempt to express precisely the fluid's induction period with respect to oxidative stability.

A test data sheet for each test reported herein is included in Volume II of this report. The data sheets are arranged in the order of test number.

SECTION II

TEST APPARATUS AND PROCEDURES

A. Test Glassware

The test sample tubes are constructed of standard wall 51-mm Pyrex® tubing with a round bottom. A standard taper 71/60 outer joint is provided at the tube top. Overall tube length is 450 ± 10 mm.

The test tube head is constructed with a standard taper 71/60 ground-glass joint on the lower end which mates with the test cell joint. The upper surface of the head is formed in a dome-shaped contour. Attached to this surface are three female ground joints. A 10/30 joint is centrally located to accommodate the air tube. A second 10/30 joint, slightly offset from center, provides for temperature measurements and intermediate sampling. Offset and at a 90-degree position from the sampling port, a 24/40 joint is attached to relieve effluent vapors. Using the condensate return procedure, a 300-mm Allihn condenser is directly attached to the latter joint. For test durations of 96 hr and less, the condenser is water cooled. Reflux tests longer than 96 hr employ forced-air cooling of a 200-mm Graham condenser at a flow of approximately 1 cfm. This procedure was adopted to allow for unattended operation during weekends without the safety hazards associated with an overhead water system. The nonreflux test procedure employs a connecting arm, with a 15-degree downward slant, between the 24/40 joint and an overboard condenser. For this work, a 200-mm water-cooled Graham condenser was used.

An air delivery tube of standard 6-mm Pyrex® tubing, approximately 600 mm in length, is fixed in the upper end of the head by means of a tapered Teflon® thermometer adapter. The tip of the air tube is cut at a 45-degree angle and rests directly on the bottom of the sample tube. A small glass collar of sufficient size to hold the metal specimen is located 15 mm from the tip of the air tube. The bottom metal specimen rests directly on this collar, and succeeding specimens are separated by glass spacers 6-mm wide, cut from standard 9-mm Pyrex® tubing.

B. Heating Units

Tests conducted at temperatures of less than 425°F utilized three thermostated oil baths. Test cell immersion depth in these units is approximately 250 mm. Tests conducted at 425°F and above employed an aluminum block heat medium. Cell immersion depth with this unit, previously described in detail[(1)], is 250 mm, plus 100 mm of adjacent (top) insulation.

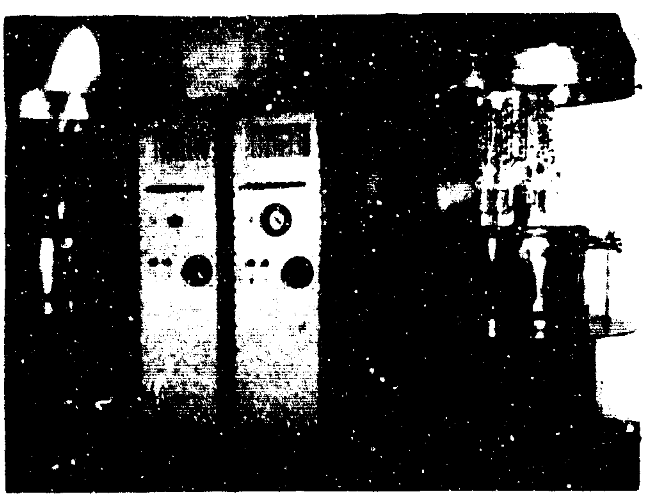

Figure 1. Circular Oil Baths and Control Panel

The three oil baths employed in this work include a rectangular, six-cell unit previously described.[(2)] Due to the increased number of experiments desired, two additional units of circular configuration were fabricated. These units, shown in Figure 1, will accommodate a maximum of eight test cells each using either a nonreflux glassware configuration or a reflux configuration (Fig. 1) in which the vapor condensers are attached directly above the sample tubes.

The circular baths are equipped with a heavy duty stirrer to provide bath oil agitation. Bath heating is achieved by means of a 1500-watt circular immersion heater in conjunction with a 750-watt heater of the same design. The 1500-watt

(1) **Development of Lubricant Screening Tests and Evaluation of Lubricants for Gas Turbine Engines for Commercial Supersonic Transport**, ASD Technical Documentary Report 63-264, Part I, March 1963.
(2) **Oxidation-Corrosion Characteristics of Aircraft Turbine Engine Lubricants**, AFAPL Technical Report 66-7, February 1966.

unit is a continuously-on element controlled by a variable transformer which is adjusted for optimum control during operation. The 750-watt element is controlled by an adjustable thermister switch to obtain the final temperature trim. The baths are capable of temperatures from about 250°F up to 500°F. The bath fluid is a 5P4E polyphenyl ether lubricant (used) accumulated from various tests conducted at this laboratory.

C. Air Supply System

A precision air regulator is used to provide a constant air pressure to individual fine-thread needle valves from the laboratory air line. The air is passed through a drying column, containing a calcium sulfate drier, then to a manifold before reaching the individual test tube control valves and flowmeters. Each of the air flowmeters was checked by means of water displacement calibrations in order to provide accurate measurement of the airflow rate.

D. Metal Test Specimens

The metal corrosion specimens are of the round washer type with dimensions 3/4-in. OD and 1/4-in. ID by 0.032-in. thickness. The following material designations apply to the metals which were used:

Aluminum	QQ-A-250/4, temper T-3 or T-4
Silver	MIL-S-13282 (ord), Grade A
Copper	QQ-C-576
Mild Steel	AMS 5040
Magnesium	QQ-M-44 (AZ31B)
Titanium	AMS 4908
Stainless Steel	MIL-S-5059 (ASG), grade 301, half-hard
Bronze	SAE-CA674

E. Test Procedures

As previously indicated, test conditions employed in this program were varied extensively. In order to outline these various procedures, Table I summarizes the pertinent conditions and techniques used. All temperatures cited herein refer to sample temperature, not the heat medium temperature which is normally 2 to 3°F higher.

All lubricant samples were analyzed to determine kinematic viscosity at 100 and 210°F and neutralization number. In evaluations using the nonreflux apparatus, the overhead fluid was analyzed for 100°F viscosity and neutralization number. Metal specimen attack was determined by weight difference. In addition, the coupons were examined at a 20X microscope magnification to observe the type of metal corrosion, e.g., pitting or etching.

Prior to use, the metal specimens were prepolished with 240 grit silicon carbide abrasive paper. Final finishing was performed with 400 grit paper. The individual specimens were then cleaned by benzene-wetted cotton swab, followed by acetone-wetted cotton swab.

Post-test preparation of the metal specimens included a successive rinse in benzene and acetone to remove oil. The individual specimens were benzene swabbed using a series of cotton swabs until clean swabs were noted. The coupons were finally rinsed in benzene and acetone, air dried, and weighed.

For several tests, an electrocleaning procedure was employed following the normal specimen cleanup. The individual metals, except aluminum, were cathodically cleaned in a hot (170 to 190°F) caustic bath. The bath contained an aqueous solution of 15 g/liter sodium hydroxide and 15 g/liter trisodium phosphate. The coupons were cleaned as the cathode for a period of 15 to 30 sec using a current density of 0.5 amp/in^2. After removal from the bath, the specimens were rinsed in cold water and cotton swabbed to remove loose deposits. The metals were weighed after a final rinse in acetone. The aluminum specimens were soaked in concentrated nitric acid for a period of 15 min, then rinsed and processed as described above.

Table 1. Oxidation-Corrosion Test Conditions and Procedures

Sample temperature	347°F	347°F	365°F	375°F	385°F	392°F	401°F	428°F	428°F	425 & 450°F	464°F	600°F	608°F	608°F	644°F	650°F	680°F
Duration	96-192 hr	26 day	9-14 day	48 hr	48 hr	72 hr	72 hr	48 hr	168 hr	18 hr	48 hr	48 hr	48 hr	168 hr	48 hr	48 hr	48 hr
Air rate, liters/hr	10	10	10	130	10, 130	10	10	10	10	130	10	20	10, 130	10	10, 130	20	10
Reflux	Yes	Yes	Yes	No	Both	Yes	Yes	Yes	Yes	No	Yes	No	Both	Yes	Both	No	Yes
Sample charge, ml	200	200	200	200	200	200	200	200	200	200	200	250	200	200	200	250	200
Intermediate sampling time	48, 96, 144 hr	7, 14, 21 day	7, 8, 9, 10, 11 day	16, 24, 40 hr	16, 24, 40 hr	24, 40, 48, 64 hr	24, 40, 48, 64 hr	16, 24, 40 hr	72, 120 hr	None	16, 24, 40 hr	16, 24, 40 hr	16, 24, 40 hr	72, 120 hr	16, 24, 40 hr	16, 24, 40 hr	16, 24, 40 hr
Intermediate sample vol, ml	20	35	35	20	20	20	20	20	20	None	20	20	20	20	20	20	20
Sample makeup, ml	None	35	35	None	None	None	None	None	None	None	None	None	None	None	None	None	None
Metal specimen set*	I	I, II, III, VII	I	I	I	I	I	I, II	II	V	II	V, VI	I, II, III, IV	I, II	I, II, III, IV	V, VI	I, II, III

*Metal specimen set I: Al, Ti, Ag, steel, Cu, Mg.
II: Al, Ti, Ag, steel, Cu.
III: Al, Ti, Ag, steel.
IV: Al, Ti, Ag, steel, S.S., Cu.
V: Al, Ti, Ag, steel, S.S.,
VI: Al, Ti, Ag, steel, S.S., Cu, Mg.
VII: Al, Ti, Ag, steel, bronze, Mg.

Test glassware deposits and sludge were likewise recorded. After test, the entire sample was filtered through a 200-mesh screen to observe bulk sludge deposits. A 25-ml portion of the lubricant sample was then subjected to a 1-hr centrifuging at a relative force of 840 g's in order to measure suspended sludge.

F. Lubricant Performance Criteria

Lubricant oxidation-corrosion test studies traditionally utilize the sample performance criteria of viscosity change and neutralization number. In a majority of tests described herein, these measures of lubricant performance were applied in assessing fluid stability. However, for certain test series, the feasibility of applying an alternate set of indices of lubricant performance, i.e., the "viscosity breakpoint" and "neutralization number breakpoint," was also explored.

The "breakpoints" are defined in this report as the duration of test time required for either the lubricant viscosity or the neutralization number to reach certain assigned rates of increase. Thus, a breakpoint based upon the rate of viscosity increase is called the "viscosity breakpoint," and that based upon the rate of increase of neutralization number is called the "neutralization number breakpoint." Because of the significant variance in test durations reported herein and, consequently, degradation rates, the breakpoints were differently defined according to test time. Tests of 9-day duration and longer were subject to the following breakpoint definitions:

(1) Viscosity–time (days) for the 100°F viscosity to reach a rate of increase of 1 cs/4 days

(2) Neutralization number–time (days) for the neutralization number to reach a rate of increase of 1 mg KOH/g/4 days.

All tests of lesser duration were subject to the following breakpoint definitions:

(1) Viscosity–time (hr) for the 100°F viscosity to reach a rate of increase of 1 cs/8 hr

(2) Neutralization number–time (hr) for the neutralization number to reach a rate of increase of 1 mg KOH/g/8 hr.

For the latter category, actual test times ranged from 48 to 192 hr.

Figure 2 presents a plot of data obtained in a 72-hr test at 401°F on lubricant O-64-12. The graphs scales are selected such that the tangent to the plotted curve yields a slope of one at the defined degradation rate. Viscosity and neutralization number breakpoints were identified for this example at 52 and 41 hr, respectively. It will be noted that both viscosity and acidity accelerated rapidly once the breakpoints were attained. This phenomenon is typical of deterioration trends of a large majority of tests conducted in this program, and was a significant factor in fixing the breakpoint definitions previously given.

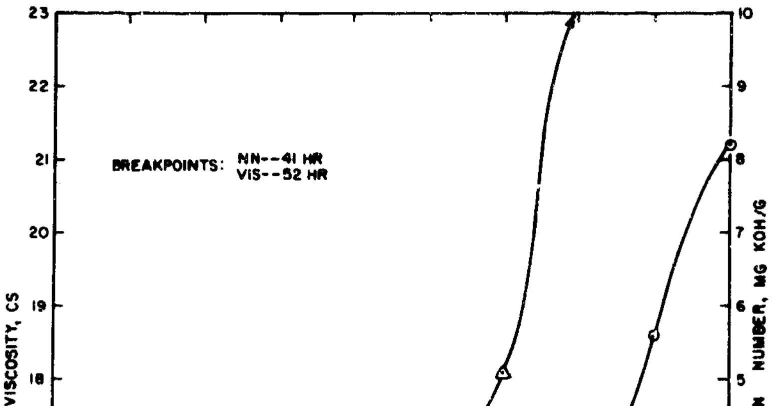

Figure 2. Typical Lubricant Breakpoint Determinations

SECTION III

TEST LUBRICANTS

A total of 119 lubricants and 22 lubricant blends were evaluated in the test program. Table 2 presents a listing of the lubricants employed in this program, along with initial viscosity and neutralization number data and available information on lubricant types.

Table 2. Description of Test Lubricants

Oil Code	Viscosity, cs		Neut. No., mg KOH/g	Description
	100°F	210°F		
O-60-8	16.1	4.2	0.18	MIL-L-7808 E
O-60-18	12.1	3.2	0.19	MIL-L-7808 E
O-61-11	15.7	4.1	0.39	MIL-L-7808 E
O-61-17	15.7	3.6	0.04	MIL-L-9236 B
O-62-3	15.5	3.8	0.02	MIL-L-7808 G
O-62-4	15.0	3.9	0.11	MIL-L-7808 E
O-62-6	17.8	4.7	0.24	MIL-L-007808 F
O-62-7	17.4	4.2	0.01	MIL-L-7808 type
O-62-13	16.0	4.2	0.25	MIL-L-7808 E
O-62-16	16.8	4.4	0.22	MIL-L-7808 E
O-62-25	15.6	3.5	0.06	MIL-L-9236 B
O-63-1	17.5	4.6	0.23	MIL-L-7808 type
O-63-2	16.3	4.3	0.22	MIL-L-7808 type
O-63-3	15.2	4.1	0.24	MIL-L-7808 type
O-63-8	13.8	3.5	0.15	MIL-L-7808 E
O-63-16	16.5	4.3	0.29	MIL-L-7808 E
O-64-1	26.0	5.1	0.10	MIL-L-27502 type
O-64-2	27.5	5.1	0.07	MIL-L-23699
O-64-6	14.7	3.6	0.18	MIL-L-7808 type
O-64-12	13.8	3.5	0.25	MIL-L-7808 D
O-64-13	28.4	5.3	0.28	MIL-L-23699
O-64-17	28.4	5.3	0.33	MIL-L-27502 type
O-64-18	16.8	4.3	0.11	MIL-L-7808 E
O-64-20	24.2	4.1	0.00	Aromatic ether, experimental
O-64-21	15.6	3.6	0.07	MIL-L-7808 type
O-64-22	18.3	4.1	0.17	MIL-L-7808 type
O-64-25	28.8	5.4	0.00	MIL-L-23699
O-64-26	12.8	3.1	0.33	MIL-L-7808 type
O-65-7	74.7	6.0	0.25	Experimental
O-65-14	17.7	4.7	0.24	Different batch of O-62-6
O-65-15	27.2	5.0	0.02	MIL-L-23699
O-65-16	26.7	5.1	0.20	MIL-L-23699
O-65-18	17.6	4.6	0.21	Different batch of O-62-6
O-65-19	17.7	4.7	0.25	Different batch of O-62-6
O-65-20	17.8	4.7	0.26	Different batch of O-62-6
O-65-21	15.1	3.8	0.07	Different batch of O-62-3
O-65-22	15.2	3.7	0.00	MIL-L-7808 type
O-65-23	12.6	3.2	0.20	MIL-L-7808 type
O-65-25	14.7	3.7	0.07	Different batch of O-62-3
O-65-31	13.4	3.2	0.08	MIL-L-7808 G
O-65-33	18.1	4.1	0.14	MIL-L-7808 type
O-65-35	13.1	3.2	0.21	MIL-L-7808 type

Table 2. Description of Test Lubricants (Cont'd)

Oil Code	Viscosity, cs		Neut. No., mg KOH/g	Description
	100°F	210°F		
O-65-36	28.3	5.3	0.14	MIL-L-23699
O-65-37	14.3	3.4	0.33	MIL-L-7808 type
O-65-38	14.3	3.5	0.11	MIL-L-7808 type
O-65-39	15.6	4.1	0.27	MIL-L-7808 type
O-65-40	13.7	3.3	0.11	MIL-L-7808 type
O-65-44	16.2	4.3	0.27	MIL-L-27502 type
O-66-1	12.9	3.2	0.27	MIL-L-7808 type
O-66-2	13.8	3.3	0.05	Same as O-66-9
O-66-3	16.3	4.3	0.14	MIL-L-7808 type
O-66-5	15.0	3.8	0.05	Different batch of O-62-3
O-66-9	13.9	3.3	0.06	Different batch of O-67-11
O-66-10	348.0	12.9	0.00	Formulated polyphenyl ether 5P4E
O-66-11	16.4	4.3	0.16	MIL-L-7808 type
O-66-14	26.0	5.0	0.01	MIL-L-23699
O-66-15	28.6	5.4	0.14	Different batch of O-65-36
O-66-16	26.0	5.0	0.01	MIL-L-23699
O-66-25	13.6	3.3	0.10	MIL-L-7808 type
O-66-26	274.5	26.3	--	Experimental (fluorinated)
O-67-1	357.6	13.0	0.01	Different batch of O-66-10
O-67-2	14.4	3.6	0.21	MIL-L-7808 type
O-67-3	12.8	3.1	0.24	MIL-L-7808 type
O-67-4	29.2	5.4	0.10	MIL-L-27502 type
O-67-5	13.6	3.3	0.22	Different batch of O-65-31
O-67-6	13.4	3.3	0.03	MIL-L-7808 type
O-67-7	17.3	4.6	0.26	Different batch of O-62-6
O-67-8	13.2	3.3	0.23	MIL-L-7808 type
O-67-9	14.8	3.7	0.04	Different batch of O-62-3
O-67-10	17.3	4.6	0.26	Different batch of O-62-6
O-67-11	13.3	3.2	0.05	MIL-L-7808 G
O-67-13	13.5	3.2	0.10	MIL-L-7808 type
O-67-19	12.5	3.2	0.12	MIL-L-7808 type
O-67-20	13.5	3.2	0.21	Different batch of O-65-31
O-67-21	12.9	3.2	0.14	MIL-L-7808 type
O-67-24	13.0	3.5	0.24	MIL-L-7808 G
O-68-1	13.3	3.2	0.00	MIL-L-7808 type
O-68-5	16.3	4.0	0.20	MIL-L-7808 type
O-68-6	13.1	3.2	0.29	MIL-L-7808 type
ATL-401	26.3	5.1	0.11	MIL-L-27502 type
ATL-402	46.8	8.2	0.12	MIL-L-27502 type
ATL-405	34.4	6.3	0.09	MIL-L-27502 type
ATL-556	14.0	3.6	1.66	MIL-L-7808 (used)
ATL-561	14.4	3.8	–	MIL-L-7808 (used)
ATL-584	16.2	4.1	0.15	Blend (1:1) of O-65-18 and O-65-21
ATL-652	15.6	3.5	0.19	MIL-L-9236 B (used)
ATL-719	16.4	4.0	5.86	MIL-L-7808 (used)
ATL-720	13.3	[illegible].4	0.38	MIL-L-7808 (used)
ATL-737	14.0	3.5	3.57	MIL-L-7808 (used)
ATL-753	13.7	3.5	0.23	MIL-L-7808 (used)
ATL-769	15.0	3.8	0.04	MIL-L-7808 type
ATL-770	15.0	3.8	0.04	MIL-L-7808 type
ATL-771	15.0	3.7	0.04	MIL-L-7808 type
ATL-7725	13.7	3.5	0.50	MIL-L-7808 (used)
ATL-7727	13.7	3.3	0.16	MIL-L-7808 type

Table 2. Description of Test Lubricants (Cont'd)

Oil Code	Viscosity, cs 100°F	Viscosity, cs 210°F	Neut. No., mg KOH/g	Description
ATL-802	15.1	3.6	2.04	MIL-L-7808 type (used)
ATL-805	14.6	3.8	0.41	MIL-L-7808 (used)
ATL-806	14.3	3.5	0.45	MIL-L-7808 (used)
ATL-807	13.8	3.6	0.34	MIL-L-7808 (used)
ATL-808	13.4	3.4	0.39	MIL-L-7808 (used)
ATL-809	13.4	3.4	0.36	MIL-L-7808 (used)
ATL-810	13.9	3.6	0.32	MIL-L-7808 (used)
ATL-814	13.4	3.4	0.23	MIL-L-7808 (used)
ATL-825	14.1	3.6	4.26	MIL-L-7808 (used)
ATL-829	13.9	3.5	0.27	MIL-L-7808 (used)
ATL-830	13.6	3.4	0.80	MIL-L-7808 type (used)
ATL-831	14.5	3.5	0.28	MIL-L-7808 (used)
ATL-832	13.8	3.4	0.31	MIL-L-7808 (used)
ATL-833	13.5	3.5	2.22	MIL-L-7808 (used)
ALO-716-P625893	14.5	3.6	3.29	MIL-L-7808 (used)
ALO-717-P628985	13.9	3.5	1.57	MIL-L-7808 (used)
ALO-718-F622807	13.3	3.35	0.68	MIL-L-7808 (used)
MLO-62-1005	41.8	6.8	0.11	MIL-L-27502 type
MLO-62-1011	14.7	3.4	0.02	MIL-L-9236 B type
MLO-62-1012	26.9	5.3	0.37	MIL-L-27502 type
MLO-63-1002	46.8	8.2	0.16	MIL-L-27502 type
F-1041	354.5	12.9	0.00	Polyphenyl ether, 5P4E mixed isomers
G-1033	351.6	13.0	0.03	Same as F-1041
J-1115	16.3	4.2	0.17	Blend (1:1) of O-65-19 and O-65-21
J-1116	15.7	4.0	0.12	Blend (1:3) of O-65-19 and O-65-21
J-1117	17.0	4.4	0.20	Blend (3:1) of O-65-19 and O-65-21
J-1118	15.3	3.8	0.09	Blend (1:9) of O-65-19 and O-65-21
J-1119	17.4	4.6	0.23	Blend (9:1) of O-65-19 and O-65-21
J-1126	16.2	4.1	0.16	Blend (1:1) of O-65-18 and O-65-21
J-1127	15.6	4.0	0.12	Blend (1:3) of O-65-18 and O-65-21
J-1128	16.9	4.4	0.20	Blend (3:1) of O-65-18 and O-65-21
J-1129	15.3	3.8	0.09	Blend (1:9) of O-65-18 and O-65-21
J-1130	17.3	4.5	0.22	Blend (9:1) of O-65-18 and O-65-21
K-1004	16.1	4.1	0.17	Blend (1:1) of O-65-19 and O-65-25
K-1005	15.4	3.9	0.12	Blend (1:3) of O-65-19 and O-65-25
K-1006	16.9	4.4	0.20	Blend (3:1) of O-65-19 and O-65-25
K-1007	15.0	3.8	0.09	Blend (1:9) of O-65-19 and O-65-25
K-1008	17.4	4.5	0.23	Blend (9:1) of O-65-19 and O-65-25
K-1051	390.6	13.3	0.00	Polyphenyl ether, 5P4E type
K-1054	16.3	4.2	0.16	Different batch of J-1115
L-1129	15.0	3.7	0.05	Blend (1:1) of ATL-769 and ATL-771
L-1136	16.1	4.1	0.15	Blend (1:1) of O-67-7 and O-67-9
M-1041	71.3	6.9	0.09	Blend (1:1) of O-64-20 and O-67-1
M-1051	13.8	3.4	0.08	Blend (1:1:1) of O-67-9, O-67-11, and O-67-20
M-1052	13.6	3.4	0.16	Blend (1:1:1:1) of O-67-9, O-67-11, O-67-20, and O-67-24
M-1053	13.7	3.3	0.12	Blend (1:1:1:1) of O-67-9, O-67-11, O-67-20, and O-68-1

SECTION IV

TEST RESULTS AND DISCUSSION

A. General Remarks

The subsequent discussion of results is divided into two broad categories according to test temperature. Evaluations performed with conventional and advanced ester-type formulations were carried out within a temperature range of 347 to 464°F. Studies conducted with experimental type fluids, such as polyphenyl ethers and variations thereof, covered a range of temperatures from 600 to 680°F.

The effects of various test conditions were explored in both categories. In the lower temperature range, a major objective was the investigation of relative performance ranking when comparing short duration, high temperature (385 to 401°F) data with long duration test results at 347°F. This study was directed toward examination of the validity of accelerated testing, i.e., the tradeoff of temperature for time. The principle of lubricant breakpoint was first applied in this study, with neutralization number breakpoint being the primary criterion.

It should be noted that several of the high-airflow (130 liters/hr) tests included herein were previously reported.[2] Where applicable, these data are repeated here in order to provide a more comprehensive picture of lubricant performance.

B. Test Results in the Range 347 to 464°F

1. *18-Hr Oxidation-Corrosion Test Results.* The 18-hr test procedure employed in this series was originally developed[1,3] to provide reasonable correlation with 425°F engine tests conducted by AFAPL. The procedure utilizes an airflow rate of 130 liters/hr with the nonreflux glassware configuration. Metal specimen set V (Al, Ti, Ag, steel, and S.S.) is employed in this procedure.

Table 3 summarizes the results of this series performed with six lubricants. The objective of the work was to determine the lubricants' temperature tolerance with respect to oxidation stability by increasing the test temperature from an initial value of 425°F, in 25°F increments, until a sample viscosity increase at 100°F of 100 percent or more was obtained. In Table 3, lubricants O-65-16 and ATL-652 reached this level of degradation at 425°F while O-64-21, O-64-22, O-64-25, and O-65-15 showed a 100°F viscosity increase in excess of 100 percent at 450°F. On the basis of viscosity increase, lubricant O-65-15 gave the best performance; this oil, along with O-64-25, also showed the best performance on the basis of neutralization number. Significant metal attack was noted only for silver in the 450°F test on O-64-25. Lubricant O-65-15 indicated the best overall performance of the lubricants evaluated at 450°F, while O-64-22 indicated the best performance at 425°F.

2. *Test Results in the Range 385 to 401°F.* A total of 51 test lubricants were evaluated in an extensive test series at 385°F using a 48-hr procedure. This series utilized three basic sets of test conditions—130 liters/hr airflow with reflux, 130 liters/hr nonreflux, and 10 liters/hr reflux. The normal metal specimen group for all tests was set I (Al, Ti, Ag, steel, Cu, and Mg). A summary of data obtained in this series is given in Table 4.

In Table 4, attention is particularly called to the test airflow rate of 130 liters/hr which was used in both reflux and nonreflux tests. As a consequence of the relatively high airflow, condensation efficiency was very low. Thus, only slight refluxing was actually obtained when using the condensate return configuration. This fact is substantiated by oil loss data which indicated little or no difference in sample weight loss between reflux and nonreflux tests on the test fluids at 385°F. However, when the reflux test was performed at 10 liters/hr, a significant effect was obtained. Sample weight loss for these tests was less than 10 percent in all cases.

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(3) Development of Lubricant Screening Tests and Evaluation of Lubricants for Gas Turbine Engines for Commercial Supersonic Transport, ASD Technical Documentary Report 63-264, Part II, May 1965.

Table 3. Summary of 18-Hr Oxidation-Corrosion Test Results

(Air rate, 130 liters/hr; nonreflux)

Oil Code	Test Temp, °F	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
O-64-21	425	36	3.93	24	None	149-1
	450	5080	15.10	68	None	150-1
O-64-22	425	6	0.57	22	None	149-2
	450	1235	9.99	65	None	150-2
O-64-25	425	16	1.05	11	None	188-1
	450	2700	8.38	50	Ag	189-1
O-65-15	425	19	0.81	17	None	188-2
	450	722	8.80	38	None	189-2
O-65-16	425	122	6.80	20	None	188-3
ATL-652	425	99	6.97	40	None	271-1
	425	115	7.21	42	None	271-2

*Defined as a weight change of ±0.20 mg/cm^2, or more. Metal set V (Al, Ti, Ag, steel, S. S.).

Table 4. Summary of 48-Hr, 385°F Test Results on Several Lubricants

Oil Code	Air Rate, liters/hr	Condensate Return	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
O-60-8	130	No	390	1.67	60	None	127-1
	10	Yes	6	13.91	4	Cu	230-1
O-60-18	130	No	25	1.10	50	All	127-2
	130	No	25	0.98	50	None	200-3
	130	Yes	31	1.00	52	None	200-4
	10	Yes	6	2.13	2	Cu	230-2
O-61-11	130	No	118	1.38	54	Ag, Cu	143-1
	130	No	88	1.17	60	Steel, Cu	127-3
	10	Yes	-4	8.39	3	None	227-5
O-62-3	130	No	72	1.21	42	None	127-4
	130	Yes	69	1.08	43	None	166-1
	130	Yes	73	1.12	43	None	163-1
	10	Yes	0	1.54	2	None	230-3
O-62-4	130	No	101	1.45	58	None	143-2
	130	No	113	1.95	55	None	127-5
	130	Yes	79	1.14	54	None	164-1
	10	Yes	0	1.91	3	Mg	230-4

Table 4. Summary of 48-Hr, 385°F Tests Results on Several Lubricants (Cont'd)

Oil Code	Air Rate, liters/hr	Condensate Return	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
O-62-6	130	No	118	22.4	57	Cu	127-6
	130	No	119	2.06	57	None	165-1
	130	No	129	1.78	58	None	143-3
	130	Yes	58	5.01	54	None	164-2
	130	Yes	49	10.78	54	Cu	163-2
	10	Yes	−12	5.30	3	Cu	230-5
O-62-13	130	No	144	1.54	57	None	137-1
	10	Yes	−6	2.86	3	Cu	232-2
O-62-16	130	No	70	13.96	57	None	137-2
	130	Yes	110	21.9	57	Cu	163-3
	10	Yes	−9	6.42	3	None	227-3
O-63-8	130	No	20	0.50	35	Cu	137-3
	10	Yes	7	1.63	2	Cu	232-6
O-63-16	130	No	170	1.14	56	None	137-4
	130	Yes	153	1.17	55	None	163-4
	10	Yes	−4	1.99	2	None	227-6
O-64-2	130	No	19	0.38	15	None	143-6
	130	Yes	18	0.31	16	None	164-3
	10	Yes	15	0.41	4	None	226-1
O-64-6	130	No	31	3.20	35	Ag, Cu, Mg	195-4
	130	Yes	30	3.28	34	Ag, Cu, Mg	195-1
O-64-12	130	No	14	1.27	31	Al, Ti, Ag, steel, Mg	143-4
	130	No	14	1.48	30	Ag, steel, Mg	255-1
	10	Yes	7	2.10	2	Ti	226-2
O-64-18	130	No	27	1.69	36	None	137-5
	130	No	27	2.58	35	None	255-2
	10	Yes	−2	5.13	3	None	226-3
O-64-26	130	No	109	0.41	54	Cu†	168-1
	130	Yes	106	0.47	52	Cu	167-1
	10	Yes	11	0.52	3	None	226-6
O-65-14	130	No	577	28.9	60	None	181-1
	130	Yes	452	30.7	58	None	181-2
	130	Yes	4866	22.3	58	Mg, Mg‡	224-2
	10	Yes	5	13.07	5	Cu, Mg	223-1
	10	Yes	−8	11.90	4	Cu, Mg	255-3
	10	Yes	−3	1.63	4	None‡	224-1

Table 4. Summary of 48-Hr, 385°F Test Results on Several Lubricants (Cont'd)

Oil Code	Air Rate, liters/hr	Condensate Return	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
O-65-18	130	No	148	1.85	59	None	183-1
	130	No	80	14.44	56	None	201-6
	130	No	177	1.66	59	None	202-4
	130	Yes	129	1.68	54	None	183-2
	130	Yes	227	28.0	57	Cu	202-3
	130	Yes	143	1.13	54	Mg, Mg‡	224-4
	10	Yes	–9	8.84	2	Cu	223-2
	10	Yes	–9	3.83	1	Mg, Mg‡	224-3
O-65-19	130	No	59	1.29	45	None	183-3
	130	No	167	1.91	58	None	200-1
	130	Yes	48	10.49	52	None	183-4
	10	Yes	–11	8.02	3	Cu	223-3
O-65-20	130	No	144	1.77	57	None	222-2
	130	Yes	122	1.80	56	None	222-1
	10	Yes	–11	10.47	3	Cu	255-4
O-65-21	130	No	76	1.25	45	None	183-5
	130	No	82	1.21	47	None	200-2
	130	Yes	174	26.4	54	Cu, Mg	183-6
	10	Yes	0	1.63	3	None	223-4
O-65-22	130	No	15	1.23	27	None	195-5
	130	Yes	15	1.21	27	Mg	195-2
O-65-23	130	No	141	0.84	52	None	191-3
	130	Yes	148	0.86	50	None	191-1
	10	Yes	9	1.18	3	None	227-1
O-65-25	130	No	78	1.30	48	Cu	208-3
	130	Yes	79	1.33	47	None	208-1
	10	Yes	1	1.62	3	None	223-5
O-65-31	130	No	59	0.65	43	None	192-6
	130	No	72	0.74	47	None	208-4
	130	Yes	58	0.65	44	None	192-3
	130	Yes	62	0.74	44	None	208-2
	10	Yes	9	0.93	1	None	223-6
O-65-33	130	No	10	0.38	24	None	213-4
	130	Yes	10	0.37	24	None	213-1
O-65-35	130	No	108	0.92	44	Mg	195-6
	130	Yes	105	0.91	44	Mg	195-3
	10	Yes	11	1.41	3	None	227-4

Table 4. Summary of 48-Hr, 385°F Test Results on Several Lubricants (Cont'd)

Oil Code	Air Rate, liters/hr	Condensate Return	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
O-65-36	130	No	18	0.45	12	Mg	196-4
	130	Yes	17	0.50	11	Mg	196-1
O-65-37	130	No	26,560 (40 hr)	24.3 (40 hr)	51	Cu	213-5
	130	Yes	19,000 (40 hr)	24.3 (40 hr)	49	Cu	213-2
	10	Yes	84	10.20	6	Cu, Mg	227-2
O-65-38	130	No	72	0.20	46	Mg	196-5
	130	Yes	66	0.23	46	Mg	196-2
O-65-39	130	No	238	1.99	62	None	214-4
	130	Yes	1025	3.29	61	None	214-1
O-65-40	130	No	64	0.67	43	Mg	196-6
	130	Yes	61	0.75	43	Mg	196-3
	10	Yes	9	0.93	3	None	226-4
O-66-1	130	No	98	0.84	44	None	213-6
	130	Yes	98	0.86	45	None	213-3
O-66-2	130	No	93	0.96	47	None	214-5
	130	Yes	73	0.94	44	None	214-2
	10	Yes	9	1.14	1	None	224-5
O-66-3	130	No	209	1.68	58	None	214-6
	130	Yes	223	1.76	60	None	214-3
O-66-5	130	No	70	1.53	45	Mg	255-6
	10	Yes	-2	1.84	7	None	255-5
O-66-9	130	No	77	0.96	44	None	275-3
	10	Yes	9	1.14	2	None	226-5
O-66-11	130	No	780	47.9	45	Cu, Mg	225-2
	130	Yes	635	45.2	44	Cu	225-1
	10	Yes	13	13.57	4	None	224-6
O-66-25	130	No	157	2.09	51	Cu	253-4
	10	Yes	17	2.73	3	Cu	253-1
O-67-2	130	No	34	0.63	40	None	253-5
	10	Yes	0	0.94	2	None	253-2
O-67-3	130	No	54	1.05	42	Mg	253-6
	10	Yes	9	1.36	1	None	253-3

Table 4. Summary of 48-Hr. 385°F Test Results on Several Lubricants (Cont'd)

Oil Code	Air Rate, liters/hr	Condensate Return	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
0-67-4	130	No	19	0.62	10	Cu	269-4
	10	Yes	12	0.57	4	Cu	269-1
	10	Yes	12	0.53	5	Cu	291-1
0-67-5	130	No	65	0.80	47	None	269-5
	10	Yes	9	1.09	0	None	269-2
0-67-7	130	No	173	1.68	59	None	269-6
	10	Yes	−12	6.65	2	None	269-3
0-67-8	130	No	91	1.56	54	Cu	268-4
	10	Yes	12	1.57	4	Cu	268-1
	10	Yes	12	1.50	5	None	291-3
0-67-9	130	No	81	1.11	47	None	268-5
	10	Yes	0	1.36	3	None	268-2
0-67-10	130	No	298	15.49	61	Mg	275-4
	10	Yes	−6	13.20	8	Cu, Mg	275-1
0-67-11	130	No	169	0.88	53	None	268-6
	10	Yes	9	1.11	3	None	268-3
0-67-13	130	No	50	0.42	46	Mg	275-5
	10	Yes	10	0.75	2	Cu	275-2
	10	Yes	10	0.59	3	Cu	291-4
ATL-556	130	Yes	730	27.0	59	Cu	202-1
ATL-561	130	Yes	572 (40 hr)	39.2	64	Cu	202-2
ATL-584	130	No	98	1.49	54	None	197-2
	130	Yes	96	1.50	51	None	197-1

*Defined as a weight change of ±0.20 mg/cm², or more. Metal set I (Al, Ti, Ag, steel, Cu, Mg).
†After electrocleaning procedure.
‡Metal specimen set used: Mg, Mg.

In Table 4, viscosity and neutralization number for the 130 liters/hr tests are compared. A large majority of the lubricants examined in this study were unaffected by the reflux procedure. However, some fluids showed a possible effect, and the technique served both to improve or worsen performance depending on oil type. Lubricants O-62-4, O-62-6, O-65-19, and O-66-2 showed increased oxidative stability when run with the reflux procedure. The use of condensate return had a deleterious effect on the performance of O-62-16, O-65-18, O-65-21, and O-65-39. For all lubricants mentioned, the effect was reflected by sample viscosity. Lubricant O-65-19 gave poor repeatability in a repeat test using the nonreflux procedure. The second test yielded a threefold increase in viscosity. The neutralization number obtained with the reflux procedure was considerably higher than nonreflux values although the viscosity increase was close to the first nonreflux test result.

Metal specimen corrosion data in the 130-liters/hr reflux determinations were, with one exception, generally unchanged from the results shown in nonreflux tests. Lubricant O-65-21, which gave no significant metal attack in nonreflux oxidation-corrosion tests, showed weight losses of 0.27 and 0.73 mg/cm^2 for copper and magnesium, respectively. The lubricant was of the group which likewise showed increased deterioration of oil properties using condensate return.

Many of the lubricants evaluated at 130-liters/hr airflow were also tested at an air rate of 10 liters/hr using the condensate return procedure. From Table 4, it is seen that the 130-liters/hr airflow had a much greater effect on viscosity than neutralization number. With the exception of some MIL-L-23699-type lubricants, few oils performed adequately at this high airflow; whereas, most fluids performed satisfactorily in the 10-liters/hr test. Metal specimen data, for the most part, were unchanged from the results shown in the high-airflow tests.

One procedural variation in the composition of the metal specimen set was used for lubricants O-65-14 and O-65-18. For one test at 130 liters/hr, condensate return, two magnesium metal specimens were substituted for the "standard" metal set. Sample viscosity increase was greater for O-65-14 using this variation, but neutralization number was slightly lower. Both magnesium specimens were severely attacked. Lubricant O-65-18 showed no significant change from the standard test. This variation was repeated using the 10-liters/hr reflux procedure. Lubricant O-65-14 showed essentially the same viscosity increase as in the standard test, but neutralization number was much lower, with no attack of the magnesium specimens appearing. Similarly, O-65-18 gave a lower neutralization number, but both magnesium specimens were attacked.

Using the high-airflow, nonreflux test procedure, a systematic study was conducted to examine the effect of blending selected lubricants. Various volumetric concentrations were tested at 375 and 385°F using the following lubricant combinations: O-65-18 and O-65-21; O-65-19 and O-65-21; and O-65-19 and O-65-25. The three lubricant combinations cited are actually blends of different batches of the same two formulations. Reference to Table 2 shows that O-65-18 and O-65-19 are different batches of O-62-6, whereas O-65-21 and O-65-25 are different batches of O-62-3.

As shown in Table 5, viscosity and acidity data for the 375°F tests indicated a closely similar performance for the constituent lubricants, as well as the various mixtures. At 385°F, however, the O-65-18/O-65-21 combination demonstrated a significant and unusual incompatibility for two specific blend concentrations. Figure 3 illustrates the deleterious effect obtained for the blends containing 10 and 25 volume percent of O-65-21. Unexplainably, the 385°F blend series with O-65-19 (different batch of O-65-18) and O-65-21 did not produce the same effect. This phenomenon suggests a possible inconsistency between the O-65-18 and O-65-19 sample batches.

In a subsequent test series at moderate temperatures, the low-airflow (10 liters/hr) reflux conditions were maintained throughout. In addition, the lubricant breakpoint criteria were applied for all runs. Numerous evaluations, summarized in Table 6, were performed at one or more of the three test temperatures of 385, 392, and 401°F. A 48-hr test duration was observed in a majority of tests; however, several runs were extended to 72 hr to increase the probability of breakpoint occurrence.

As previously mentioned, the neutralization number breakpoint was considered to be the primary performance criterion. This parameter almost invariably occurred slightly earlier than the corresponding viscosity breakpoint, using the rate of change definitions established.

Reference to Table 6 reveals that many of the lubricants examined at 385°F gave relatively high neutralization number breakpoints, or none at all. Most of the exceptions to this observation were used oil samples. As expected, a much greater performance spread occurred for the various fluids evaluated at 392 and 401°F. At these higher temperatures, certain lubricants exhibited a marked sensitivity to temperature increase. In addition, the response to temperature change was not consistent among the lubricants evaluated. The phenomenon is illustrated by the following test data for O-60-18 and O-67-9:

	Sample Temp, °F	Neut. No. Breakpoint, hr
O-60-18	385	61
	392	53
	401	18
O-67-9	385	55
	392	44
	401	33

Table 5. 48-Hr Oxidation-Corrosion Test Results for Selected Lubricant Blends

(Air rate, 130 liters/hr; nonreflux)

Content, vol %		375°F Sample Temperature			385°F Sample Temperature		
		100°F Vis Increase, %	Neut. No., mg KOH/g	Test No.	100°F Vis Increase, %	Neut. No., mg KOH/g	Test No.
O-65-18	O-65-21						
100	0	67	0.90	204-6	135*	5.98*	*
90	10	80	0.96	204-5	506	14.12	201-5
75	25	60	0.99	204-3	232	18.64	201-3
50	50	71	0.97	204-1	101†	1.48†	†
25	75	64	0.95	204-2	87	1.31	201-2
10	90	68	0.86	204-4	92	1.29	201-4
0	100	60	0.88	205-6	79‡	1.23‡	‡
O-65-19	O-65-21						
100	0	65	0.94	203-6	113**	1.60**	**
90	10	75	0.95	203-5	130	2.00	199-5
75	25	57	0.93	203-3	94	1.67	199-3
50	50	66	0.95	203-1	106	1.48	199-1
25	75	60	0.85	203-2	86	1.34	199-2
10	90	67	0.80	203-4	90	1.23	199-4
0	100	60	0.88	205-6	79‡	1.23‡	‡
O-65-19	O-65-25						
100	0	65	0.94	203-6			
90	10	73	1.07	205-5			
75	25	61	1.05	205-3			
50	50	66	0.98	205-1			
25	75	60	0.91	205-2			
10	90	64	0.91	205-4			
0	100	57	0.94	207-1			

*Average of three determinations; Tests Nos. 183-1, 201-6, and 202-4.
†Average of two determinations; Tests Nos. 197-2 and 201-1.
‡Average of two determinations; Tests Nos. 183-5 and 200-2.
**Average of two determinations; Tests Nos. 183-3 and 200-1.

At 385 and 392°F, O-60-18 demonstrated a greater stability as evidenced by neutralization number breakpoint. At 401°F, however, the lubricant gave a significantly shorter breakpoint and was less satisfactory than O-67-9 at this temperature.

As described in Table 6, lubricants O-65-14 and O-65-18 (different batches of the same formulation) were examined at 385°F using modified test conditions. The normal metal specimen set was omitted and two magnesium specimens were inserted. This variation of metal types produced several unusual performance effects. With magnesium alone, viscosity data for O-65-14 were essentially unchanged. However, there was a noticeable improvement in stability as reflected by sample acidity. The neutralization number breakpoint was increased, and the final 48-hr neutralization number was appreciably lower. A contrast was also shown for the O-65-14 corrosion

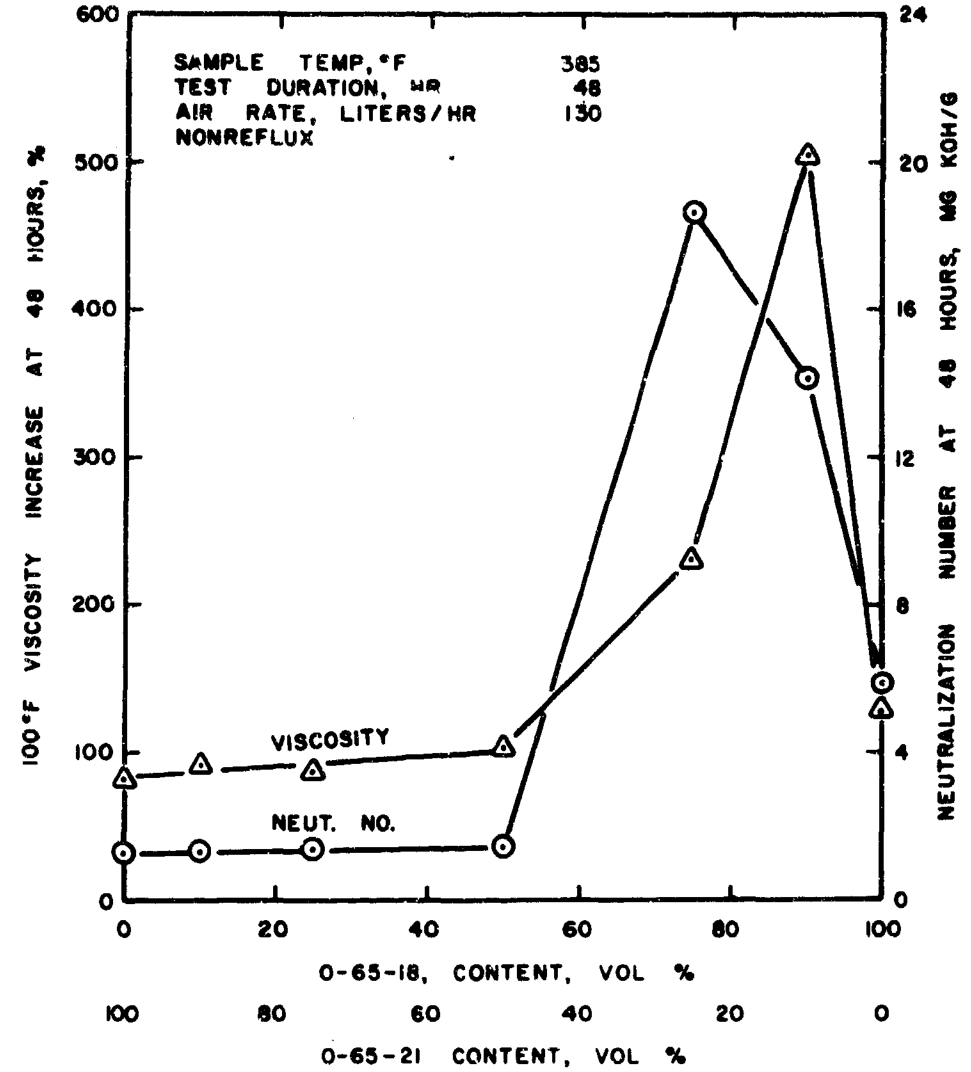

Figure 3. 385°F Oxidation-Corrosion Test Results on the Effect of Blending Lubricants O-65-18 and O-65-21

data. Significant weight losses for magnesium were recorded for both determinations using the normal metal set. In the test with magnesium alone, neither of the two coupons indicated significant attack.

O-65-18 showed the reverse effect with respect to corrosion data. Magnesium attack did not occur in the standard test, whereas, with the dual magnesium specimens, both coupons indicated significant corrosion. Sample property results for O-65-18 showed an effect for the metal variation similar to that obtained with O-65-14, except that the neutralization number improvement with magnesium alone was less pronounced with the former oil.

Seven of the lubricant samples listed in Table 6 consisted of equal volume blends of various constituent oils. Breakpoint data for the tests are grouped in Table 7 according to the constituent oil data and the corresponding blend (K-, L-, and M-coded samples) data. Although many determinations showed no deterioration breakpoints within the test period, the blend results revealed no apparent incompatibility between constituents. This conclusion is somewhat tentative in the case of L-1136, since data at 401°F were not obtained for O-67-7. However, the 385°F test results for the L-1136 constituents imply that the blend result at 401°F is within the expected breakpoint range of the constituents.

Table 6. Summary of Low-Airflow Reflux Oxidation-Corrosion Test Results

(Air rate 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Test Time, hr	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, hr 100°F Vis	Breakpoint, hr Neut. No.	Significant Metal Attack*	Test No.
O-60-8	385	48	6	13.91	44	28	Cu	230-1
O-60-18	385	48	6	2.13	48+	48+	Cu	230-2
	385	72	10	6.29	72+	61	All	325-1
	392	72	50	21.6	54	53	All	296-1
	401	72	93	29.9	41	18	All except Mg	327-1
O-61-11	385	48	−4	8.39	48+	39	None	227-5
O-62-3	385	48	0	1.54	48+	48+	None	230-3
O-62-4	385	48	0	1.91	48+	48+	Mg	230-4
O-62-6	385	48	−12	5.30	48+	40	Cu	230-5
O-62-7	385	48	−1	1.26	48+	48+	None	230-6
	385	48	0	1.13	48+	48+	None	232-1
O-62-13	385	48	−6	2.86	48+	46	Cu	232-2
O-62-16	385	48	−9	6.42	48+	38	None	227-3
O-63-1	385	48	−10	3.78	48+	40	None	232-3
O-63-2	385	48	−7	3.90	48+	43	None	232-4
O-63-3	385	48	3	12.43	48+	40	Cu, Mg	232-5
O-63-8	385	48	7	1.63	48+	48+	Cu	232-6
O-63-16	385	48	−4	1.99	48+	48+	None	227-6
O-64-2	385	48	15	0.41	48+	48+	None	226-1
	392	72	19	0.55	72+	72+	None	312-1
	392	72	18	0.63	72+	72+	None	326-1
	401	72	22	1.61	72+	72+	None	314-1
O-64-12	385	48	7	2.10	48+	48+	Ti	226-2
	385	72	6	3.07	72+	72+	Al, steel	325-2
	392	72	11	7.56	72+	60	All except Cu	296-2
	401	72	54	20.5	52	41	All	314-2
O-64-18	385	48	−2	5.13	48+	40	None	226-3
	392	72	46	23.4	43	18	Cu	296-3
O-64-26	385	48	11	0.52	48+	48+	None	226-6

Table 6. Summary of Low-Airflow Reflux Oxidation-Corrosion Test Results (Cont'd)

(Air rate 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Test Time, hr	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, hr 100°F Vis	Breakpoint, hr Neut. No.	Significant Metal Attack*	Test No.
O-65-14	385	48	–5	13.07	45	31	Cu, Mg	223-1
	385	48	–8	11.90	48+	41	Cu, Mg	255-3
	385†	48	–3	1.63	48+	48+	None	224-1
	392	72	1445	24.4	41	30	Cu, Mg	296-4
O-65-18	385	48	–9	8.84	48+	40	Cu	223-2
	385†	48	–9	383	48+	42	Mg, Mg	224-3
O-65-19	385	48	–11	8.02	48+	39	Cu	223-3
	392	72	32	19.89	56	28	Cu, Mg	296-5
O-65-20	385	48	–11	10.47	48+	40	Cu	255-4
O-65-21	385	48	0	1.63	48+	48+	None	223-4
	385	72	14	10.14	65	56	Cu	325-3
	392	72	30	16.22	54	49	Cu	297-1
	401	72	65	21.7	40	18	Cu	314-3
O-65-23	385	48	9	1.18	48+	48+	None	227-1
O-65-25	385	48	1	1.62	48+	48+	None	223-5
O-65-31	385	48	9	0.93	48+	48+	None	223-6
	392	72	14	1.57	72+	72+	Mg	326-2
	401	72	17	2.09	72+	72+	Mg	327-2
O-65-35	385	48	11	1.41	48+	48+	None	227-4
O-65-37	385	48	84	10.20	8	6	Cu, Mg	227-2
O-65-40	385	48	9	0.93	48+	48+	None	226-4
O-66-2	385	48	9	1.14	48+	48+	None	224-5
O-66-5	385	48	–2	1.84	48+	48+	None	255-5
O-66-9	385	48	9	1.14	48+	48+	None	226-5
O-66-11	385	48	13	13.57	41	31	None	224-6
	385	72	[illegible]	23.3	40	24	Cu, Mg	325-4
	392	72	62	23.8	30	24	Cu, Mg	297-2
O-66-25	385	48	17	2.73	48+	48+	Cu	253-1
O-67-2	385	48	0	0.94	48+	48+	None	253-2

Table 6. Summary of Low-Airflow Reflux Oxidation-Corrosion Test Results (Cont'd)

(Air rate 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Test Time, hr	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, hr		Significant Metal Attack*	Test No.
					100°F Vis	Neut. No.		
O-67-3	385	48	9	1.36	48+	48+	None	253-3
	385	72	10	1.35	72+	72+	None	325-5
	392	72	12	1.81	72+	72+	None	312-2
	392	72	11	1.80	72+	72+	None	326-3
	401	72	50	10.58	56	56	None	314-4
O-67-4	385	48	12	0.57	48+	48+	Cu	269-1
	385	48	12	0.53	48+	48+	Cu	291-1
O-67-5	385	48	9	1.09	48+	48+	None	269-2
O-67-6	385	48	10	1.11	48+	48+	None	291-2
O-67-7	385	48	–12	6.65	48+	39	None	269-3
	392	72	835	31.0	41	19	Cu, Mg	312-3
O-67-8	385	48	12	1.57	48+	48+	Cu	268-1
	385	48	12	1.50	48+	48+	None	291-3
	392	72	18	3.44	72+	70	Cu	326-4
O-67-9	385	48	0	1.36	48+	48+	None	268-2
	385	72	13	10.90	66	55	Cu	325-6
	392	72	32	16.98	53	44	Cu	312-4
	401	72	74	22.6	40	33	Cu	314-5
O-67-10	385	48	–6	13.20	45	26	Cu, Mg	275-1
O-67-11	385	48	9	1.11	48+	48+	None	268-3
	392	72	13	1.84	72+	72+	None	312-5
	401	72	73	11.88	54	46	None	314-6
O-67-13	385	48	10	0.75	48+	48+	Cu	275-2
	385	48	10	0.59	48+	48+	Cu	291-4
O-67-19	385	48	8	2.30	48+	48+	None	295-1
	385	48	8	2.56	48+	48+	Cu	307-1
	392	72	11	3.68	72+	72+	None	326-5
	401	72	14	5.33	72+	71	None	327-3
O-67-20	385	48	10	0.85	48+	48+	None	295-2
	385	48	9	0.91	48+	48+	Cu	307-2
	392	72	13	1.37	72+	72+	None	297-3
	401	72	38	9.03	61	55	None	314-7
O-67-21	385	48	9	0.92	48+	48+	None	295-3
	392	72	12	1.57	72+	72+	None	312-6
	401	72	16	2.33	72+	71	None	327-4

Table 6. Summary of Low-Airflow Reflux Oxidation-Corrosion Test Results (Cont'd)

(Air rate 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Test Time, hr	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, hr 100°F Vis	Breakpoint, hr Neut. No.	Significant Metal Attack*	Test No.
O-67-24	385	48	2	2.50	48+	48+	Steel, Cu	307-3
	385	72	18	16.08	64	53	Mg	325-7
	392	72	60	33.3	53	40	Cu, Mg	312-7
	401	72	86	34.6	40	15	Cu, Mg	327-5
O-68-1	385	48	8	0.79	48+	48+	Steel, Cu	307-4
	392	72	11	1.29	72+	72+	None	312-8
	401	72	19	3.61	71	66	None	314-8
O-68-5	385	48	4	1.03	48+	48+	None	334-5
O-68-6	385	48	35	9.48	36	26	Cu	335-1
ATL-719	385	48	20	19.54	36	20	Cu	318-1
ATL-720	385	48	25	14.08	38	29	Cu	318-2
ATL-737	385	48	5	3.44	48+	48+	None	318-3
ATL-753	385	48	4	1.39	48+	48+	Cu	318-4
ATL-769	385	48	-1	1.20	48+	48+	None	291-5
ATL-770	385	48	-1	1.26	48+	48+	None	291-6
ATL-771	385	48	0	1.23	48+	48+	None	291-7
ATL-7725	385	48	45	22.5	28	17	Cu	308-7
ATL-7727	385	48	8	0.83	48+	48+	None	298-1
ATL-805	385	48	6	3.99	48+	45	Cu	308-1
ATL-806	385	48	14	9.00	42	36	None	308-2
ATL-807	385	48	21	15.79	38	28	Cu	308-3
ATL-808	385	48	14	7.68	43	40	Cu	308-4
ATL-809	385	48	14	7.05	43	40	Cu	308-5
ATL-810	385	48	18	15.87	40	30	Cu	308-6
ATL-814	385	48	38	11.36	32	25	Cu	323-1
ATL-825	385	48	26	20.4	34	25	Cu	323-2

Table 6. Summary of Low-Airflow Reflux Oxidation-Corrosion Test Results (Cont'd)

(Air rate 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Test Time, hr	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, hr 100°F Vis	Breakpoint, hr Neut. No.	Significant Metal Attack*	Test No.
ATL-829	385	48	3	1.77	48+	48+	None	334-1
ATL-830	385	48	28	9.68	40	30	None †	334-2
ATL-831	385	48	7	1.01	48+	48+	None	334-3
ATL-832	385	48	8	1.10	48+	48+	None	334-4
ATL-833	385	48	4	4.35	48+	48+	None	335-2
ALO-716	385	48	9	839	46	37	Cu, Mg	303-1
ALO-717	385	48	6	3.75	48+	46	Cu	303-2
ALO-718	385	48	36	21.1	30	28	Cu	303-3
K-1054	392	72	29	21.8	52	36	Cu, Mg	297-4
L-1129	385	48	−1	1.28	48+	48+	None	295-4
L-1136	385	48	−6	2.04	48+	47	None	295-5
	401	72	91	32.0	34	17	Cu, Mg	327-6
M-1051	385	48	5	0.85	48+	48+	None	315-1
M-1052	385	48	5	1.46	48+	48+	None	315-2
M-1053	385	48	6	0.82	48+	48+	None	315-3

*Defined as a weight change of ±0.20 mg/cm^2, or more. Metal set 1 (Al, Ti, Ag, steel, Cu, Mg).
†Metal specimen set used: Mg, Mg.

Table 7. Breakpoint Data for Lubricant Blends and Blend Constituents

(Air rate, 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Breakpoint, hr 100°F Vis	Breakpoint, hr Neut. No.	Oil Code	Sample Temp, °F	Breakpoint, hr 100°F Vis	Breakpoint, hr Neut. No.
O-65-19	392	56	28	O-67-7	385	48+	39
O-65-21	392	54	49	O-67-9	385	66	55
K-1054	392	52	36	O-67-20	385	48+	48+
				M-1051	385	48+	48+
ATL-769	385	48+	48+				
ATL-771	385	48+	48+	O-67-9	385	66	55
L-1129	385	48+	48+	O-67-11	385	48+	48+
				O-67-20	385	48+	48+
O-67-7	385	48+	39	O-67-24	385	64	53
O-67-9	385	66	55	M-1052	385	48+	48+
L-1136	385	48+	47				
				O-67-9	385	66	55
O-67-7	401	---	---	O-67-11	385	48+	48+
O-67-9	401	40	33	O-67-20	385	48+	48+
L-1136	401	34	17	O-68-1	385	48+	48+
				M-1053	385	48+	48+

3. *Long-Duration Test Results.* A frequent question relating to the applicability of lubricant bench tests concerns the validity of accelerated testing procedures. The objective of test acceleration is obvious—a greater number of samples may be screened with attendant savings of time and costs. The question is whether the use of test acceleration produced valid screening data. In the case of the oxidation-corrosion test, the question can be stated in terms of the increased temperature required to shorten test duration, i.e., can a 48-hr or 72-hr test at, say, 392°F effectively predict relative oil performance under service conditions of lower temperatures and much longer durations? The results discussed in this section of the report constitute a brief examination of this aspect of the oxidation-corrosion test.

Using the low-airflow reflux procedure, five lubricants were examined in the initial test series at 347°F. As shown in Table 8, sample degradation in all instances was very slight for test durations ranging from 96 to 192 hr. No deterioration breakpoints occurred at any condition.

The low-airflow reflux procedure was next employed in a series using a 26-day (624-hr) test duration, also at 347°F. With this extended test period, the intermediate sampling schedule was modified to allow for weekly sampling intervals. Intermediate sample volumes of 35 ml were taken, and were replaced with new oil at each sampling period.

Summary data for the 26-day test series are given in Table 9. Although only a limited number of repetitive runs were made, the repeatability of the procedure appeared to be satisfactory with two exceptions. There was poor correspondence for neutralization number breakpoint in repeat tests with lubricants O-65-14 and O-65-19. For both oils, however, there was good agreement of viscosity breakpoint data in repeat tests.

Several procedural variations were employed in the 26-day series, primarily with regard to the composition of the metal specimen set. One determination on O-65-14 was performed without oil makeup for intermediate samples. This deviation, as expected, promoted lubricant deterioration in comparison with data for the normal procedure. Lubricant O-65-18 was examined in one run without the magnesium specimen present. The deletion resulted in an appreciable increase in the viscosity breakpoint and a slight increase in the neutralization number breakpoint. These effects, however, may not be too significant in view of the extremely rapid deterioration of O-65-18, both with and without magnesium, subsequent to the fluid's induction period. Nonstandard tests with O-65-19 included one without copper or magnesium and one in which copper was replaced by a bronze specimen. In both instances, lubricant performance was considerably improved. Thus, the extreme degradation of O-65-19 in standard determinations would appear to be attributable to the presence of the pure copper specimen. The same effect was not produced by bronze, although the metal has a high copper content (58 percent, typical). The determination on O-65-21, with copper and magnesium excluded, showed no appreciable performance change from that obtained from one of the standard tests. Three specimen set variations were employed with lubricant O-66-25. As with O-65-19, the presence of copper resulted in increased oxidative degradation for O-66-25. The use of bronze did not produce any significant catalytic effect on sample deterioration.

Table 9 contains results for one equal-part blend examined in the 26-day series. Blend K-1054 was made up of the constituents O-65-19 and O-65-21. The K-1054 determination indicated no incompatibility of the mixture, but showed a performance approximating that of the better constituent, viz. O-65-21.

Table 10 lists the results of a brief test series at an intermediate test-condition severity. Six lubricants were examined at 365°F for test durations ranging from 9 to 14 days. The resultant test data showed the time-temperature conditions to be generally inapplicable. Three of the test fluids gave very short, indeterminate neutralization number breakpoints, whereas the remaining three lubricants showed no breakpoints within the 14-day test period.

Table 8. Summary of Oxidation-Corrosion Tests at 347°F, 96 to 192 Hr

(Air rate, 10 liters/hr; reflux)

Test Duration, hr	100°F Vis Change, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
O-65-14					
96	−2.0	1.10	3	None	210-1
144	−1.3	1.29	5	None	211-1
192	−2.3	1.56	6	None	212-1
192	−2.6	1.54	4	None	212-2
O-65-18					
96	−1.6	1.10	2	None	210-2
144	−2.1	1.25	2	None	211-2
192	−1.6	1.50	6	Cu	212-3
O-65-19					
96	−1.9	1.13	2	None	210-3
144	−2.0	1.31	3	None	211-3
192	−3.1	1.60	4	None	212-4
O-65-21					
96	+3.0	0.91	3	None	210-4
144	+2.3	1.01	3	None	211-4
192	+3.7	1.17	6	None	212-5
O-65-25					
96	+1.6	1.01	2	None	210-5
144	+3.1	0.96	4	None	211-5
192	+1.4	1.26	2	None	212-6

*Defined as a weight change of ±0.20 mg/cm², or more. Metal set I (Al, Ti, Ag, steel, Cu, Mg).

A comparison of neutralization number breakpoint data obtained under equivalent test conditions, other than time and temperature, is given in Table 11. The test lubricants are listed in order of decreasing performance capability at 347°F. The resultant ranking of lubricants generally indicates very satisfactory correspondence between the long-duration test results and those for the higher temperature, short-duration tests. One possible exception to this agreement might be O-67-24. Short-duration test results with this oil imply a higher ranking than that allowed by the 13-day breakpoint obtained at 347°F. However, considering the repeatability of the 26-day test, the O-67-24 discrepancy may not be real. For example, a breakpoint variation of +2 days could have moved the O-67-24 ranking to a position between K-1054 and O-66-25. In this position, the short-duration test data for O-67-24 would show much improved alignment. Further, it should be recalled that the 347°F, 26-day test procedure employs a different breakpoint definition from that of the short-duration test, as well as sample oil makeup. It is expected that the latter variation in technique might demonstrate a pronounced effect on the oxidative stability of certain lubricants.

Table 9. Summary of 26-Day, 347°F Oxidation-Corrosion Test Results

(Air rate 10 liters/hr; reflux)

Oil Code	Metal Specimen Set*	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, days		Significant Metal Attack†	Test No.
				100°F Vis	Neut. No.		
O-60-18	Standard	5	2.29	26+	26+	All	293-1
O-64-2	Standard	20	0.51	26+	26+	Mg	261-6
	Standard	20	0.42	26+	26+	None	294-1
O-64-12	Standard	6	2.78	26+	26+	All	293-2
O-64-18	Standard	1	5.45	26+	14	None	293-3
O-65-14	Standard	68,898 (21 days)	61.9	17	6	Cu, Mg	241-2
	Standard	67 (21 days)	50.5	14	17	Cu, Mg	283-1
	Standard‡	82 (14 days)	72.6 (21 days)	8	5	Cu	241-1
O-65-18	Standard	13 (21 days)	53.0	16	14	Cu, Mg	248-1
	w/o Mg	−7 (21 days)	53.4	23	17	Cu	248-2
O-65-19	Standard	267 (21 days)	54.1	15	14	Cu	241-3
	Standard	7 (21 days)	52.4	19	13	Cu	248-3
	Standard	−11 (14 days)	48.3	14	5	Cu, Mg	283-2
	w/o Cu, Mg	−5	2.32	26+	26+	None	261-4
	Bronze in place of Cu	−4	2.33	26+	26+	None	261-5
O-65-21	Standard	18	9.78	23	18	Cu	241-4
	Standard	5	2.46	26+	26+	Cu	261-2
	w/o Cu, Mg	3	2.38	26+	26+	None	248-4
O-65-31	Standard	16	0.85	26+	26+	Cu	241-5
	Standard	18	0.91	26+	26+	None	261-1
O-66-9	Standard	13	0.85	26+	26+	None	277-4
O-66-11	Standard	982 (21 days)	53.6	10	10	Cu, Mg	293-4
O-66-25	Standard	72	5.69	16	14	Ag, Cu	241-6
	w/o Mg	87	7.87	9	11	Ag, Cu	248-5
	w/o Cu, Mg	18	1.91	26+	26+	Ag	248-6
	Bronze in place of Cu	19	1.65	26+	26+	Ag	261-3
O-67-3	Standard	16	0.74	26+	26+	None	324-1
O-67-7	Standard	12 (21 days)	25.0 (21 days)	16	14	Cu, Mg	294-2
O-67-8	Standard	18	1.84	26+	26+	Cu	294-3

Table 9. Summary of 26-Day, 347°F Oxidation-Corrosion Test Results (Cont'd)

(Air rate 10 liters/hr; reflux)

Oil Code	Metal Specimen Set*	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, days 100°F Vis	Breakpoint, days Neut. No.	Significant Metal Attack†	Test No.
0-67-9	Standard	5	1.55	26+	26+	None	277-5
	Standard	5	1.39	26+	26+	Cu	283-3
	Standard	6	2.25	26+	26+	None	324-2
0-67-11	Standard	13	0.85	26+	26+	Mg	277-6
	Standard	14	0.90	26+	26+	None	294-4
0-67-13	Standard	26	0.55	26+	26+	Cu	294-5
0-67-20	Standard	18	0.66	26+	26+	Cu	294-6
0-67-21	Standard	16	0.95	26+	26+	None	324-3
0-67-24	Standard	177	60.3	17	13	Cu, Mg	324-4
0-68-1	Standard	16	0.80	26+	26+	None	324-5
ATL-720	Standard	529 (21 days)	51.6	13	6	Cu	277-1
ATL-737	Standard	11	3.12	26+	26+	Cu	277-3
ATL-753	Standard	7	1.73	26+	26+	Cu	277-2
ATL-769	Standard	2	1.54	26+	26+	None	283-4
	Standard	4	1.54	26+	26+	Cu	293-5
ATL-770	Standard	4	1.35	26+	26+	None	283-5
ATL-771	Standard	2	1.45	26+	26+	None	283-6
K-1054	Standard	0	9.39	26	19	Cu	293-6

*Standard metal specimen set: Al, Ti, Ag, steel, Cu, Mg.

† Defined as a weight change of ±0.20 mg/cm².

‡ No oil makeup for samples.

Table 10. Summary of 365°F Oxidation-Corrosion Test Results

(Air rate 10 liters/hr; reflux)

Oil Code	Test Time, days	100°F Vis Increase, %	Neut. No., mg KOH/g	Breakpoint, days		Significant Metal Attack*	Test No.
				100°F Vis	Neut. No.		
O-65-14	9	1663	33.3	1	†	Cu, Mg	305-1
O-65-19	11	365	20.4	4	†	Cu, Mg	305-2
O-67-7	10	1275	32.4	4	†	Cu	305-3
O-67-9	14	2	1.72	14+	14+	Cu	305-4
O-67-11	14	12	1.03	14+	14+	None	305-5
O-67-20	14	13	0.78	14+	14+	Cu	305-6

*Defined as a weight change of ±0.20 mg/cm². Metal set I (Al, Ti, Ag, steel, Cu, Mg).
†Indeterminate; breakpoint occurred between 0 and 7 days.

Table 11. Lubricant Rankings as Affected by Test Temperature

(Air rate, 10 liters/hr; reflux)

Oil Code	Neut. No. Breakpoint			
	347°F, days	385°F, hr	392°F, hr	401°F, hr
O-66-9	26+	48+		
O-67-13	26+	48+, 48+		
ATL-737	26+	48+		
ATL-753	26+	48+		
ATL-769	26+, 26+	48+		
ATL-770	26+	48+		
ATL-771	26+	48+		
O-64-2	26+, 26+	48+	72+, 72+	72+
O-65-31	26+, 26+	48+	72+	72+
O-67-21	26+	48+	72+	71
O-68-1	26+	48+	72+	66
O-67-3	26+	72+	72+, 72+	56
O-67-20	26+	48+, 48+	72+	55
O-67-11	26+, 26+	48+	72+	46
O-67-8	26+	48+, 48+	70	
O-64-12	26+	72+	60	41
O-60-18	26+	61	53	18
O-67-9	26+, 26+, 26+	55	44	33
O-65-21	18, 26+	56	49	18
K-1054	19		36	
O-66-25	14	48+		
O-64-18	14	40	18	
O-65-18	14	40		
O-67-7	14	39	19	
O-67-24	13	53	40	15
O-65-14	6, 17	31,41	30	
O-65-19	14, 13, 5	39	28	
O-66-11	10	31, 24	24	
ATL-720	6	29		

An examination of the data of Table 11 suggests that the applicability and sensitivity of the short-duration test is best realized by lubricant evaluation at more than one temperature. In this way, the lubricant's response to temperature change is obtained and the performance profile may be compared with fluids of a similar class.

4. *Test Results at 428 and 464°F.* At these rather severe sample temperatures, 22 lubricants were evaluated by means of the low-airflow reflux test procedure in the aluminum block apparatus. The test lubricants were selected on the basis of expected oxidation stability at high test temperatures. Each of the test lubricants was evaluated at a 428°F, 48-hr condition. Certain of the more stable materials were also examined at a 464°F, 48-hr condition and a 428°F, 168-hr condition.

Summarized test results for this series of runs are given in Table 12. Breakpoint analysis was not applied to this series, which was performed in the early stages of the program. Figure 4 presents the performance trend for the three test conditions, as evidenced by final neutralization number. Using an arbitrary demarcation value, the initial test condition showed 10 of the 22 lubricants with a final neutralization number of less than 5 mg KOH/g. At the 464°F, 48-hr condition, two of five test oils were in this category. Of the three lubricants examined in the 168-hr test, only MLO-62-1005 yielded a neutralization number below 5 mg KOH/g. This fluid indicated very good oxidative stability on the basis of sample acidity at all conditions. However, at the two more severe test conditions, MLO-62-1005 showed significant viscosity increases (Table 12).

Table 12. Summary of 428 and 464°F Oxidation-Corrosion Test Results

(Air rate 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Test Time, hr	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
O-61-17	428	48	27	5.19	3	Cu	290-1
	428	48	27	4.93	1	Cu	317-2
O-62-25	428	48	60	11.61	7	Cu	290-2
	428	48	63	11.60	6	Cu	317-1
O-64-1	428	48	121	5.54	6	Cu	317-4
	464	48	309	7.93	8	Cu	320-1
O-64-2	428	48	38	4.54	5	None	284-1
	428	48	33	4.28	3	None	317-5
O-64-13	428	48	28	7.51	4	Cu	317-7
O-64-17	428	48	24	0.86	5	Cu	322-1
	428	168	136	5.05	11	Cu	321-1
	464	48	39	3.15	6	Cu	320-2
O-65-7	428	48	210	3.86	4	Cu	317-6

Table 12. Summary of 428 and 464°F Oxidation-Corrosion Test Results (Cont'd)

(Air rate 10 liters/hr; reflux)

Oil Code	Sample Temp, °F	Test Time, hr	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
0-65-16	428	48	32	5.80	2	None	317-8
0-65-33	428	48	36	7.52	7	Cu	290-3
	428	48	45	10.00	15	Ag, Cu	317-3
0-65-36	428	48	24	2.80	4	Cu	284-2
	428	48	23	2.51	5	Cu	319-1
0-65-44	428	48	332	15.89	6	Cu	329-3
0-66-14	428	48	35	6.09	5	Cu	319-2
0-66-15	428	48	26	2.29	5	Cu	319-3
0-66-16	428	48	42	6.62	5	Cu	319-4
0-67-4	428	48	46	7.46	7	Cu	284-3
	428	48	34	8.11	3	Cu	319-5
ATL-401	428	48	102	5.02	7	Cu	290-4
ATL-402	428	48	63	4.26	6	Cu	290-5
ATL-405	428	48	10	3.20	4	Cu	319-6
MLO-62-1005	428	48	20	1.07	8	Cu	319-7
	428	168	112	0.45	18	Steel, Cu	321-2
	464	48	238	1.48	8	Steel, Cu	320-3
MLO-62-1011	428	48	9	1.22	3	Cu	329-1
	428	168	160	14.33	11	All	328-1
	428†	168	174 (120 hr)	22.8	17	Mg	328-2
	464	48	22	5.71	4	Al, Ag	333-1
MLO-62-1012	428	48	40	37.6	5	Cu	329-2
MLO-63-1002	428	48	66	4.50	7	Cu	319-8
	428	48	73	3.80	6	Cu	322-2
	464	48	195	6.24	8	Cu	320-4

*Defined as a weight change of ±0.20 mg/cm², or more. Metal set II (Al, Ti, Ag, steel, Cu).
†Test performed with Mg added to metal set.

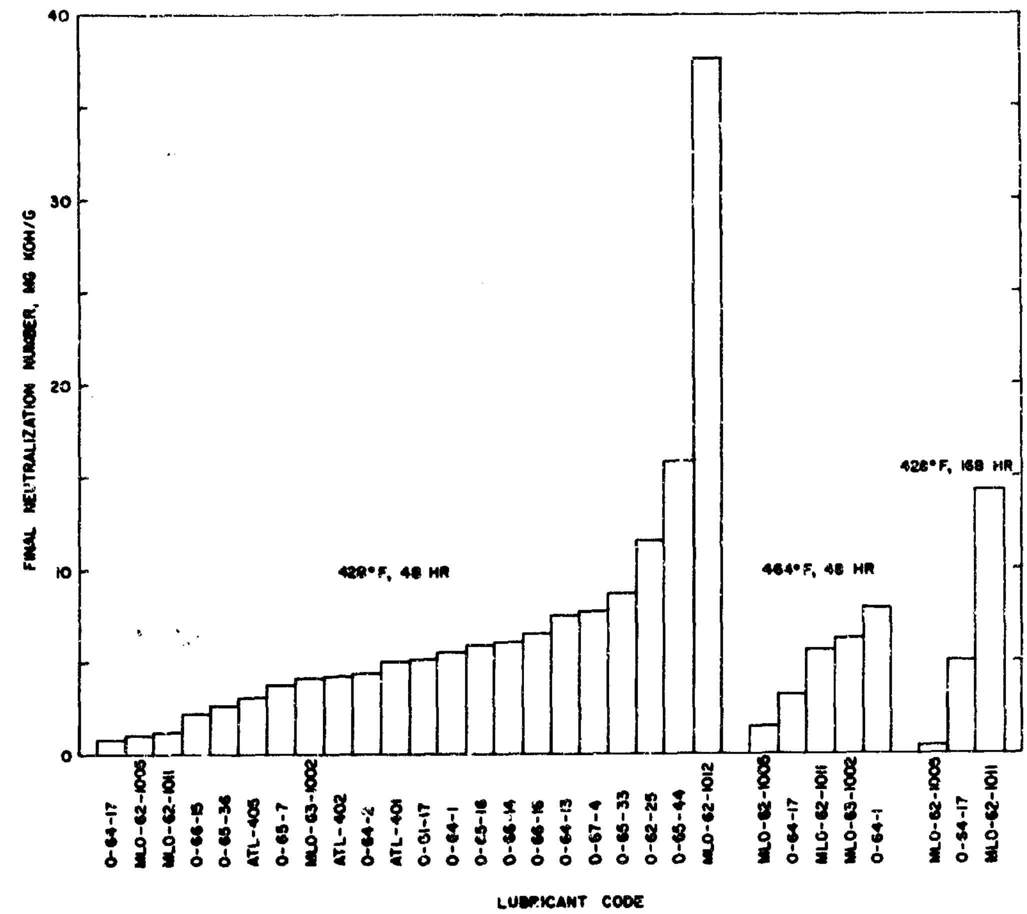

Figure 4. Neutralization Number Data for Test Temperatures
of 428 and 464°F

Copper corrosion was encountered in a large majority of the runs described in Table 12. The unusual occurrence of corrosion of mild steel as shown by MLO-62-1005 is in agreement with previous studies(3) on this fluid. At the 464°F test temperature, steel weight loss with this oil was in excess of 7 mg/cm^2. Instances of significant metal attack with MLO-62-1011 were generally associated with a weight gain due to the presence of a dark carbonaceous deposit. In the determination with magnesium added to the metal set, a lesser deposit occurred although viscosity and acidity data showed increased deterioration. The unique phenomenon of metal attack by MLO-62-1011 at the various test conditions is outlined below by weight change data given in mg/cm^2:

Metal	428°F, 48 hr	428°F, 168 hr	428°F, 168 hr	464°F, 48 hr
Al	0.00	+0.79	+0.16	+0.22
Ti	−0.06	+0.51	0.00	+0.16
Ag	0.00	+0.39	+0.04	+0.20
Steel	+0.04	+0.37	−0.06	+0.18
Cu	−1.14	−0.41	−0.18	+0.16
Mg	—	—	Destroyed	—

C. High-Temperature Test Results

Within the temperature range of 608 to 680°F, two polyphenyl ether materials and one experimental type lubricant were evaluated, primarily with respect to variation of metal types in the corrosion specimen set. The test series on the experimental fluid O-64-20 is shown in Table 13. Although significant viscosity increases occurred at the more severe test conditions, sample neutralization number remained very low throughout the series. At the 680°F temperature, sample cooling was encountered as a consequence of rapid and violent refluxing.

Table 13. Summary of High-Temperature Oxidation-Corrosion Tests on O-64-20

(Air rate 10 liters/hr; reflux)

Test Temp, °F	Test Time, hr	Metal Specimen Set	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
608	48	I	18	0.04	2	Al, Ti, steel, Cu, Mg	272-2
608	48	I	16	0.04	2	Al, steel, Cu, Mg	300-1
608	48	II	18	0.08	1	Al, Ti, steel, Cu	272-5
608	48	II	17	0.04	2	Al, steel, Cu	300-2
608	48	III	42	0.07	6	Al, Ag, steel	300-3
608	168	I	68	0.13	3	Ag, Cu, Mg	280-3
608	168	II	100	0.16	1	Ag, Cu	280-6
608	168	II	66	0.09	1	Ag, Cu	313-1
644	48	I	45	0.10	1	Ag, Cu, Mg	273-2
644	48	I	39	0.03	2	Al, Ag, steel, Cu, Mg	302-1
644	48	II	48	0.08	2	Ag, Cu	273-5
644	48	II	38	0.03	1	Al, Ag, steel, Cu	302-2
644	48	III	40	0.07	1	All	302-3
680†	48	I	156	0.01	5	Ag, steel, Cu, Mg	304-1
680†	48	II	87	0.01	5	Al, Ag, steel, Cu	304-2
680†	48	III	124	0.03	4	Al, Ag, steel	304-3

Metal set I: Al, Ti, Ag, steel, Cu, Mg
Metal set II: Al, Ti, Ag, steel, Cu
Metal set III: Al, Ti, Ag, steel

*Defined as a weight change of ±0.20 mg/cm², or more.
†Sample temperature dropped to 670°F at 16 hr and held thereafter due to violent refluxing.

The effects of metal specimen changes on O-64-20 were generally inconclusive. On the basis of viscosity data, the 48-hr/608°F conditions indicated a deleterious effect for the absence of copper (set III). However, this phenomenon was not apparent at 644°F. The 680°F condition showed a possible beneficial effect for the absence of magnesium (sets II and III); but at this viscosity level, and with an uncontrollable sample temperature, the result may be within the range of experimental repeatability.

Several instances of metal attack with O-64-20 are noted in Table 13. Copper corrosion (weight loss) was obtained in every test where the metal was present. Silver corrosion occurred at the 168-hr/608°F conditions and at the two higher test temperatures. All other notations of metal attack refer to a weight gain due to the presence of specimen deposits not removed by the normal post-test procedure.

Table 14 presents high-temperature test data for O-67-1 (a high-viscosity polyphenyl ether) and M-1041 (an equal-part blend of O-64-20 and O-67-1). Two high-airflow determinations were performed with O-67-1 and, in both cases, the tests were terminated prior to 48 hr due to severe oil losses. Thus, data shown in Table 14 for these runs

Table 14. Summary of High-Temperature Oxidation-Corrosion Tests on O-67-1 and M-1041

(Air rate 10 liters/hr; reflux)

Test Temp, °F	Test Time, hr	Metal Specimen Set	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
Lubricant O-67-1							
608†	40	IV	23 (24 hr)	0.10 (24 hr)	77	None	272-8
608	48	I	16	0.07	3	None	272-3
608	48	I	16	0.03	3	Cu	306-3
608	48	I	16	0.04	3	Cu	306-4
608	48	I	15	0.03	2	None	300-7
608	48	II	15	0.06	3	None	272-6
608	48	II	15	0.02	3	None	300-8
608	48	III	15	0.03	2	None	300-9
608	168	I	44	0.13	3	None	280-2
608	168	II	44	0.18	3	Cu	280-5
644†	24	IV	25 (16 hr)	0.04 (16 hr)	75	None	273-8
644	48	I	36	0.02	4	None	273-3
644	48	I	38	0.00	2	None	302-4
644	48	I	35	0.00	4	Cu	309-3
644	48	I	36	0.01	3	Steel	309-4
644	48	II	35	0.08	3	None	273-6
644	48	II	37	0.00	2	None	302-5
644	48	III	43	0.06	2	None	302-6
680	48	I	302	0.10	3	None	304-4
680	48	II	290	0.09	5	Cu	304-5
680	48	III	989	0.19	2	None	304-6
Lubricant M-1041							
608	48	I	21	0.02	1	Ag, Cu	310-1
644	48	I	130	0.14	2	Ag, steel, Cu, Mg	309-5

Metal set I: Al, Ti, Ag, steel, Cu, Mg
Metal set II: Al, Ti, Ag, steel, Cu
Metal set III: Al, Ti, Ag, steel
Metal set IV: Al, Ti, Ag, steel, SS, Cu

*Defined as a weight change of ±0.20 mg/cm^2 or more.
†Air rate 130 liters/hr, nonreflux.

were obtained on the penultimate samples. With the normal 10-liters/hr air rate, O-67-1 demonstrated very satisfactory oxidative stability at 608 and 644°F. The 680°F sample temperature resulted in appreciable viscosity increases, but sample acidity remained low under all conditions.

A 48-hr, four-test repeat series was performed with O-67-1 at 608 and 644°F using specimen set I. At both temperatures, the repeatability of viscosity and neutralization number data was excellent. However, results for metal specimen attack were inconsistent. Two of four determinations at 608°F showed a significant weight increase for copper. At 644°F, one determination indicated a weight gain for copper and another run gave a weight increase for mild steel. The only instances of significant metal weight loss with O-67-1 were the copper specimens noted in one 168-hr determination and in one run at 680°F.

Results for two determinations on the 1:1 blend of O-64-20 and O-67-1 (code M-1041) are also given in Table 14. At 608°F, blend performance approximated that of the least stable of the two constituents, viz., O-64-20. However, the 644°F determination indicated some incompatibility of the constituents in that sample neutralization number and, particularly, viscosity were higher than corresponding data for either constituent under comparable test conditions. Further, the 644°F test on M-1041 revealed significant corrosion of steel and magnesium, which was not shown by the constituents, as well as weight losses for silver and copper.

High-temperature test data for the 5P4E polyphenyl ether, F-1041, are listed in Table 15. As with O-67-1, the high-airflow runs on F-1041 were prematurely terminated because of excessive oil losses. In addition, many of the low-airflow determinations at the more severe conditions were terminated as a consequence of sample gellation. In comparison with O-64-20 and O-67-1, lubricant F-1041 indicated appreciable deterioration, particularly as evidenced by sample viscosity.

Table 15. Summary of High-Temperature Oxidation-Corrosion Tests on F-1041

(Air rate 10 liters/hr; reflux)

Test Temp, °F	Test Time, hr	Metal Specimen Set	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Test No.
608†	40	IV	28 (24 Hr)	0.02 (24 hr)	78	None	272-7
608	48	I	370	0.42	1	Cu, Mg	272-1
608	48	I	511	0.49	3	Ag, Cu	306-1
608	48	I	457	0.50	2	Ag, steel, Cu	306-2
608	48	I	269	0.22	3	Ag, Cu	300-4
608	48	II	270	0.38	3	Ag, Cu	272-4
608	48	II	501	0.49	7	Ag, Cu	300-5
608	48	III	1,111	0.63	3	Ag	300-6
608	168	I	1,790 (72 hr)	1.13 (72 hr)	8	Ag, Cu	280-1
608	168	II	1,226 (72 hr)	0.33 (72 hr)	7	Ag, Cu	280-4
644†	24	IV	46 (16 hr)	0.01 (16 hr)	85	None	273-7
644	48	I	5,188 (40 hr)	0.30	2	Ag, Cu, Mg	273-1
644	48	I	3,517 (40 hr)	0.34	4	Ag, Cu	316-1
644	48	I	41,490	0.38	4	Ag, Cu	309-1
644	48	I	16,355	0.35	4	Ag, steel, Cu, Mg	309-2
644	48	II	4,158 (40 hr)	0.76	3	Ag, steel, Cu	273-4

Metal set I: Al, Ti, Ag, steel, Cu, Mg
Metal set II: Al, Ti, Ag, steel, Cu
Metal set III: Al, Ti, Ag, steel
Metal set IV: Al, Ti, Ag, steel, SS, Cu

*Defined as a weight change of ±0.20 mg/cm^2 or more
†Air rate 130 liters/hr; nonreflux

The repeat tests conducted on F-1041 showed considerable variation of results for viscosity and neutralization number. However, this phenomenon is not unexpected because of the relatively high level of lubricant degradation. This variation of results was also evident in the metal attack data. In this case, some reversals were encountered with regard to specimen weight loss or gain. This is illustrated by identification of the type of metal attack (± weight change) obtained in the two, four-test series on F-1041 with metal set I:

Run No.	Significant Metal Attack	
	48 hr/608°F	48 hr/644°F
1	Cu–, Mg+	Ag–, Cu–, Mg+
2	Ag–, Cu–	Ag–, Cu–
3	Ag–, steel +, Cu+	Ag–, Cu–
4	Ag–, Cu–	Ag–, steel +, Cu–, Mg–

As a consequence of the variability of metal specimen data and the frequency of coupon deposits in the high-temperature tests, a subsequent series of runs was performed using a specimen electrocleaning procedure previously described. Several lubricants were examined in this series, with summary data given in Table 16. It will be noted that the direction of metal weight change is indicated in this table by the ± sign.

Three determinations were performed with experimental lubricant O-66-10. The fluid demonstrated good oxidative stability up to 650°F as evidenced by viscosity and neutralization number change. The variation of metal specimen set at 650°F showed essentially no effect on lubricant performance. Application of the metal specimen electrocleaning procedure revealed the presence of significant steel corrosion in two tests with O-66-10, and copper corrosion in one determination.

A single test was conducted with experimental lubricant O-66-26 (Table 16) at 600°F. A 20-percent viscosity increase was obtained on the fluid. Sample neutralization number could not be determined due to the immiscibility of the fluid in the normal toluene-isopropanol titration solvent. Lubricant O-66-26 was also unique in that significant corrosion of the titanium specimen occurred. This metal normally exhibits virtually inert characteristics in the oxidation-corrosion test, even at high temperatures.

The series on O-67-1 was performed to examine further the repeatability of the test at high temperature. Viscosity and acidity results showed excellent correspondence, and are in good agreement with previous data (Table 14) at these conditions. Metal corrosion results, however, were less satisfactory in repeatability. After electrocleaning, all four determinations on O-67-1 indicated significant copper corrosion, but only two of four showed significant silver attack.

The 5P4E polyphenyl ether, F-1041, was examined at 600 and 650°F using 20-liters/hr airflow and nonreflux. The effect of metal specimen changes (set V vs set VI) was studied at each temperature. The trend observed was the same at both temperatures; the addition of copper and magnesium (set VI) resulted in reduced viscosity and neutralization number changes, although the 650°F runs were prematurely terminated due to sample gellation.

Lubricant G-1033 shown in Table 16 is identical to F-1041. The former sample was received at a later date and, thus, assigned a distinguishing oil code number. The repeat test series at 608°F on G-1033, as well as the similar series on F-1041, showed very satisfactory repeatability of viscosity and acidity data, considering the lubricants individually or in combination. The one apparent discrepancy with respect to test agreement was the final determination on G-1033. This run did not exhibit the silver corrosion which was characteristic of earlier tests on both G-1033 and F-1041. Further discussion of metal specimen data for the O-67-1, F-1041, and G-1033 repeat test series will be given subsequently.

A single test was made with the 5P4E polyphenyl ether, K-1054, also shown in Table 16. Under comparable conditions, the fluid indicated a performance quite similar to that for F-1041, except for the occurrence of metal attack. K-1054 did not exhibit silver or copper corrosion, but did show a significant weight gain for magnesium after electrocleaning. The latter phenomenon resulted from a hard, oxide-type coating on the specimen, rather than the usual carbonaceous-type deposit.

In general, the use of metal specimen electrocleaning proved to be of considerable value. Results shown in Table 16 describe several instances of metal corrosion which were obscured by the presence of carbonaceous deposits following the normal cleaning procedure. Further, the precision of repeat test data for metal attack was improved by electrocleaning. This is illustrated by detailed weight data for silver and copper obtained in the multiple

Table 16. Summary of High-Temperature Oxidation-Corrosion Test Results - Electrocleaning Series

(Test time 48 hr)

Test Temp. °F	Air Rate, liters/hr	Condensate Return	Metal Specimen Set	100°F Vis Increase, %	Neut. No., mg KOH/g	Oil Loss, wt %	Significant Metal Attack*	Significant Metal Attack†	Test No.
Lubricant O-66-10									
600‡	20	No	V	14	0.05	8	None	None	237-4
650‡	20	No	V	46	0.05	6	None	Steel–	238-3
650‡	20	No	VI	44	0.06	12	Mg+	Steel–, Cu–	238-4
Lubricant O-66-26									
600‡	20	No	V	20	**	12	Ti–, Ag–, steel+	Ti–, Ag–, steel–	237-5
Lubricant O-67-1									
608	10	Yes	I	15	0.13	2	Cu–	Ag–, Cu–	331-5
608	10	Yes	I	15	0.14	3	Cu–	Ag–, Cu–	331-6
608	10	Yes	I	15	0.12	3	None	Cu–	330-5
608	10	Yes	I	15	0.12	2	None	Cu–	330-6
Lubricant F-1041									
600‡	20	No	V	247	0.34	8	None	None	237-1
600‡	20	No	VI	74	0.16	10	Cu+, Mg+	Cu–	237-2
608	10	Yes	I	336	0.53	3	Cu–	Ag–, Cu–	331-3
608	10	Yes	I	333	0.75	3	Ag–, Cu–	Ag–, Cu–	331-4
608	10	Yes	I	312	0.31	3	Ag–, Cu–	Ag–, Cu–	330-3
608	10	Yes	I	339	0.53	3	Ag–, Cu–	Ag–, Cu–	330-4
650‡	20	No	V	406 (16 hr)	0.70 (40 hr)	10	Ag+	Ag+, steel–	238-1
650‡	20	No	VI	211 (16 hr)	0.33 (40 hr)	7	Ag–, Mg+	Ag–, steel–, Cu–	238-2
Lubricant G-1033									
608	10	Yes	I	320	0.50	3	Ag–, Cu–	Ag–, Cu–	331-1
608	10	Yes	I	383	0.66	2	Ag–, Cu–	Ag–, Cu–	331-2
608	10	Yes	I	348	0.40	3	Ag–, Cu–	Ag–, Cu–	330-1
608	10	Yes	I	327	0.34	2	Cu–	Cu–	330-2
Lubricant K-1051									
600‡	20	No	VI	86	0.13	7	Cu+, Mg+	Mg+	237-3

*Defined as a weight change of ±0.20 mg/cm² or more after normal post-test cleaning.
†Defined as a weight change of ±0.20 mg/cm² or more after electrocleaning procedure.
‡Sample volume 250 ml.
**Sample insoluble in titration solvent.

Metal set I: Al, Ti, Ag, steel, Cu, Mg
Metal set V: Al, Ti, Ag, steel, SS
Metal set VI: Al, Ti, Ag, steel, SS, Cu, Mg

test series on O-67-1, F-1041, and G-1033, and presented in Table 17. With O-67-1, it is seen that the absolute value of the standard deviation for silver attack increased after electrocleaning. However, when expressed as a percentage of the mean, a considerable improvement in deviation was obtained by electrocleaning for both silver and copper. A similar effect was shown by the F-1041/G-1033 data, although, in this case, the improvement was less significant.

Table 17. Repeatability of High-Temperature Test Corrosion Data

(Air rate 10 liters/hr; reflux; 48 hr at 608°F; metal specimen set I.)

	Weight Change, mg/cm²			
	Normal Cleaning		Electrocleaning	
	Ag	Cu	Ag	Cu
Lubricant O-67-1				
	+0.04	−0.20	−0.26	−0.53
	+0.02	−0.24	−0.24	−0.45
	−0.06	−0.04	−0.10	−0.37
	−0.06	−0.10	−0.06	−0.47
Mean	−0.015	−0.145	−0.165	−0.455
Standard Deviation	0.053	0.091	0.100	0.066
Standard Deviation as % of Mean	353	63	61	15
Lubricants F-1041 and G-1033				
	−0.18	−1.18	−0.77	−1.46
	−0.32	−1.01	−0.43	−1.40
	−0.36	−1.03	−0.36	−1.60
	−0.36	−0.99	−0.47	−1.54
	−0.28	−1.05	−0.75	−1.44
	−0.22	−1.20	−0.69	−1.52
	−0.36	−0.95	−0.41	−1.54
	+0.02	−1.24	−0.08	−1.58
Mean	−0.258	−1.081	−0.495	1.510
Standard Deviation	0.131	0.109	0.233	0.070
Standard Deviation as % of Mean	51	10	47	5

SECTION V

CONCLUSIONS

Using an 18-hr oxidation-corrosion test procedure,[1,3] six lubricants were evaluated with respect to temperature tolerance as reflected by 100°F viscosity increase. Satisfactory performance was attributed to those lubricants which did not exceed a viscosity increase of 100 percent. On this basis, four of the six fluids were satisfactory at 425°F test temperature, but none was acceptable at 450°F.

A large number of determinations were conducted at a 385°F test temperature using airflow conditions of 130 liters/hr, reflux or nonreflux, and 10 liters/hr, reflux. Most test samples were unaffected by refluxing at the high airflow. However, certain fluids indicated improved stability, while others showed a deleterious effect for reflux of condensable vapors. All test lubricants exhibited reduced degradation rates at 10 liters/hr, in comparison with the high airflow data.

Test results at 385°F with various lubricant blends revealed some incompatibility of lubricants O-65-18 and O-65-21 at certain blend ratios. This effect points out an apparent discrepancy in lubricant batches in that the phenomenon did not occur in similar blend tests with O-65-19 and O-65-21—the former being a different batch of O-65-18.

A test series in the temperature range of 385 to 401°F was performed whereby lubricant breakpoint performance criteria were applied. With primary emphasis on neutralization number breakpoint, it is concluded that these parameters represent useful measures of lubricant performance. Furthermore, on the basis of comparisons with long-duration test data at 347°F, it is tentatively concluded that the neutralization number breakpoint obtained in short-duration, higher temperature tests will satisfactorily predict relative lubricant performance ranking. It is, however, recommended that this time-temperature relationship receive additional study for confirmation.

Within the temperature range of 385 to 401°F, several test variations were examined with respect to the composition of the metal specimen set. These variations, in many instances, resulted in significant and diverse changes in lubricant performance. The most consistent effect noted in this study was the frequency of improvement of sample stability in the absence of a pure copper specimen.

Several lubricants were evaluated at moderately severe test temperatures of 428 and 464°F. This test series was conducted prior to application of breakpoint criteria, and acceptable performance capability was described in terms of an arbitrary neutralization number value of 5 mg KOH/g. On this basis, 10 of 22 test lubricants were satisfactory at conditions of 48 hr/428°F. Final neutralization numbers at these conditions ranged from 0.86 to 37.6 mg KOH/g. At test conditions of 48 hr/464°F, only two of five fluids examined showed acidity values less than 5 mg KOH/g. Of three lubricants subjected to test conditions of 168 hr/428°F, only MLO-62-1005 showed acceptable performance as evidenced by sample neutralization number.

A number of polyphenyl ether and experimental-type fluids were evaluated in a high-temperature test series ranging from 600 to 680°F. The effects of various metal specimen sets were investigated in this series, but the performance changes due to these variations were generally inconclusive. Isolated runs, however, did show a beneficial effect for the presence of copper with 5P4E polyphenyl ether. This effect contrasts with that shown by copper in many low-temperature tests with ester-type fluids.

Several reruns were conducted in the high-temperature series to examine the repeatability of results. In all cases, very satisfactory agreement was obtained for viscosity and acid number data. However, poor agreement of metal corrosion results was observed. Subsequent determinations using metal specimen electrocleaning served to improve the precision of corrosion data, but significant deviations persisted for some tests.

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13. ABSTRACT

Results of oxidation-corrosion test evaluations on numerous aircraft turbine engine lubricants are given. Lubricant types include those related to specifications MIL-L-7808, MIL-L-9236, MIL-L-23699, and MIL-L-27502. as well as a number of experimental-type fluids such as polyphenyl ethers. Blends of selected lubricants were also examined. Test conditions were varied extensively in the study, with emphasis on the parameters of time, temperature, airflow, metals, and reflux of condensable sample vapors. A major objective in investigations with conventional, ester type lubricants was a comparison of relative performance for test series of short duration and high temperature versus long duration (26 days) and relatively low temperature. In addition, several experimental-type fluids were evaluated in a test series over a temperature range of 600 to 680°F. This investigation was mainly concerned with performance effects due to variation of metal types in the corrosion specimen set. The applicability of electrocleaning of metal specimens was also explored with regard to improvement of the repeatability of corrosion data. Volume II of this report contains a compilation of the individual test data sheets for all tests reported herein.

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